FEASIBILITY OF TRANSPORTATION PROJECTS - AN ENERGY-BASED METHODOLOGY

By

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DEDICATION

This dissertation is dedicated to my wife, Judy Hurley.

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The existing and forecasted energy shortages, the recent tendencies of oil exporting countries to use petroleum as a political weapon, and the near-total dependency of U.S. transportation on petroleum products harshly define the need of techniques by which the total energy impacts of proposed transportation projects and control strategies may be assessed. This dissertation describes and demonstrates a methodology by which these impacts may be evaluated for the large class of potential transportation improvements involving highway vehicles.

The conceptual framework recommended for comparison of proposed transportation projects is the energy-based benefit/cost ratio. This criterion was selected primarily because of its similarity to the economic benefit/cost ratio with which public officials and transportation

analysts have long been familiar due to its almost exclusive use in the transportation field. The energy-based benefit/cost analysis potentially forms a third general area to be considered in the transportation decision-making process, along with economic benefit/ cost analysis and effectiveness analysis.

The foundation for quantifying energy requirements for benefits and costs of transportation projects is based on total energy coefficients of BTU per dollar published for a 362-sector U.S. economy. These data are used to establish mathematical models and/or tables for estimating energy requirements for construction and equipment investments, operations and maintenance requirements, and road-user requirements at the project level. Data and formulae are given for construction and maintenance of highways by type and location for each of the fifty states. Running cost data are provided for three representative classes of motor vehicles. These data are presented in terms of roadway and operational characteristics. Data are provided whereby bus rapid transit operations can be considered as capital investments.

The technique is demonstrated for a bus/car pool systems demonstration project being constructed in Miami, Florida. Reasonable results were obtained, and a comparison of these results with an economic analysis for the same project showed that the two types of analysis do not necessarily indicate a common preference among candidate project alternatives.

CHAPTER I

INTRODUCTION

This dissertation describes a methodology for evaluating the feasibility of alternative transportation projects. The base standard of value is net energy rather than the monetary units traditionally used in such studies. Modal split between automobile and bus is included in the treatment.

Background and Rationale

The United States consumes more energy per capita than any other nation in the world. With only 6% of the world's population, we account for 35% of the world's energy consumption [1-3]. Forecasts indicate that our national energy demand will double approximately every 17 years [1,3-6]. Furthermore, the consumption rates for the rest of the world are growing much faster than our own. It is anticipated that the world will use as much energy from 1970 to 2000 as it did from the beginning of mankind to 1970 [1].

Energy consumed in the United States is derived from several sources. Present sources and their approximate relationships to total national energy consumption are as follows: oil (44.5%), natural gas (32%), coal (19%),

hydroelectric (4%), and nuclear (less than 1%) [1,3-5,7]. Hydroelectric power is site-restricted and will not contribute significantly to satisfaction of future demand [3,4]. Nuclear power is expected to provide slightly less than 10% of the nation's energy by 1980 [1,5] and about 17.2% in 1985 [4]. Coal, our most abundant fuel, is somewhat restricted in production by environmental regulations and safety requirements. Indications are that coal will continue to produce about 20% of our energy up to 1985 [1,4]. Domestic natural gas production in this country peaked in 1972 and has been declining since that time. The contribution of this energy source is expected to drop from 32% at the present time to 27.5% in 1980 and 19% in 1985 [1,4]. Furthermore, domestic natural gas reserves may be depleted in 20 to 25 years [4]. Of potential new energy sources, apparently none can begin to help fill the forecasted demands. Some of the more promising potential sources and their anticipated contributions are

1) Tar sands and oil shale - no more than 4% in 1990 [3]
2) Geothermal - 0.4% in 1985 [4]
3) Breeder reactor - "significant" by 2000 [4].

The only conventional energy source not discussed thus far is oil, which is expected to fulfill the remaining demand. Oil is expected to continue to supply 45 to 50% of our energy until 1985 [1,4]. However, domestic production has been declining since 1972 and even with the U.S. Artic source, which is expected to become available in 1975, production is

not expected to exceed the 1972 level [5]. Therefore, any supplies in excess of 1972 production must come from imports. The United States imported 25% of the oil it used in 1970. This is expected to increase to about 50% in 1980 [1,5] and 67% in 1990 [3].

Until recently, oil supplies have been plentiful and inexpensive. However, this source required 10^8 years to form and total world reserves can be treated as a finite amount. Worldwide consumption of oil has been doubling approximately every 10 years and recoverable world reserves (according to demand forecasts) should be depleted in 70 to 100 years [2,4]. Recoverable domestic oil should last only for 30 to 40 more years. Lovins [2] points out that all known petroleum reserves are not recoverable - only 30 to 35% of the oil in an average reservoir is now recovered. Even if this were increased to the order of 50 to 60% (which is not expected because the energy spent obtaining the oil soon exceeds that recovered), the expected lifetime of world reserves would not significantly change. Even a doubling of reserves, according to the current rate of increase of use, would extend the lifetime by only about 10 years.

The tremendous worldwide growth in energy demand, in conjunction with dwindling reserves of petroleum products and the small effects of new energy sources for at least the next 10 years, has led to the "energy crisis" which recently began but will last for quite some time. Critical

energy shortages are anticipated for the United States for the next 5 to 15 years [3,4]. Suggested long-term solutions to the problem are diverse. Some, such as Campbell [4], believe that a breakthrough into the nuclear age (if we want to accept the associated hazards) is the solution even though nuclear fuel for light water reactors may be depleted in 30 to 40 years unless the breeder reactor becomes a reality, while others, such as Odum [8], advocate returning to a low energy lifestyle (which he predicts must occur in about 20 years regardless of development of energy sources). Short-term national solutions to the problem include conservation measures and elimination of the imbalance in use of energy sources created by the substitution of inexpensive (until recently) petroleum products for coal.

United States energy use may be divided into four general categories. These catagories and their proportionate consumption of national energy are electricity generation and utilities (25%), residential and commercial (19%), industry (32%), and transportation (24%) [5,7]. The transportation sector, which is 96% dependent on petroleum [3,4,7,9], is expected to continue to account for about 25% of our national energy use until 1990 [3]. About 53% of the oil we use now is consumed by transportation [1,3,9]. One forecast [9] indicates that this will increase to 67% by 1990. Mooz [10] points out that the rate of increase of energy consumption by the transportation sector exceeds the rate of increase for the nation. Hirst [11] shows that in

1970, the automobile directly consumed 55.3% of the energy used by the transportation sector in the United States. If indirect energy costs (petroleum refining, automobile manufacturing and sales, repairs, maintenance, parts, and highway construction) are considered, then automobiles alone accounted for 21% of national energy use and 9% of the Gross National Product in 1970 [12]. Direct consumption of energy by other transportation modes in 1970 are as follows: trucks (21.1%), aircraft (7.5%), railroads (3.3%), waterways (freight only) (1.0%), pipelines (1.2%), buses (0.2%), and others, such as passenger traffic by boat, general aviation, pleasure boating, and non-bus urban mass transit (10.4%) [11].

Studies have shown that the per capita energy consumption for movement of goods has been nearly constant over the last 15 years, while per capita energy consumption for personal travel has increased about 40% [3]. While most of the increase in consumption attributable to personal travel is due to an increase in personal travel itself, it is in part due to reduced efficiency of transportation vehicles, reduced passenger loadings, and shifts to more energy-intensive modes. Mooz [10] found that from 1955 to 1968, the growth rate of energy use by transportation was about 3.9% per year - the rate for people averaged about 5% per year and that for freight averaged 2.5% per year. A study by Hirst and Herendeen [12] shows that between 1950 and 1970 automobile travel in the United States nearly tripled

while population increased by 34%. Thus, per capita auto travel increased 85% during this period. Fraize [9] states that national petroleum reserves (excluding shale) amount to only 16 times our current annual consumption of automotive petroleum. Campbell [4] visualizes petroleum-fueled internal combustion engines through 1985, and even if the conventional Otto-cycle engine is entirely superseded by another engine or system, another 10 years or so would be required for inventory turnover. Zraket [6] envisions electrification of rail systems, urban autos, and mass transit in the 1980s and 1990s. It should be noted, however, that a change to electrically powered automobiles is not expected to provide a savings in net energy. The conventional automobile is inefficient from the standpoint of converting gasoline into useful work, while at the same time the process for extracting, refining, transporting, and retailing gasoline is a relatively efficient one. On the other hand, electrically powered vehicles are expected to be efficient energy converters. Unfortunately, the conversion of energy at the generating plant is inefficient - slightly over 30% presently and another 8.5% of the energy is lost in transmission [4]. The net result is that, from a total energy standpoint, the efficiencies of the conventional automobile and the electrically powered vehicle that some expect to replace it are nearly the same (about 15%) [3].

In 1970, automobiles carried over 95% of our urban passenger traffic and more than 85% of intercity traffic [12].

It would appear as though a change of modes from automobile to mass transit would provide significant energy savings. For example, Hirst and Herendeen [12] estimate that in 1970, buses were more than twice as energy efficient as automobiles. If one considers the efficiency of a transportation mode to be the product of the efficiency of the vehicle system itself (in terms of vehicle miles per unit of energy) and the efficiency of system use (passenger miles per vehicle mile) then it is apparent that increasing bus occupancy will make that mode even more energy efficient. However, the nation's mass transit systems do not have the capacity to accommodate a large modal shift. According to Blake and Cook [7], present transit systems can only accommodate an average increase in ridership of 15%, and the national requirements to provide service for the additional riders created by a hypothetical 20% diversion of automobile commuters to transit would include 26,500 more transit vehicles, 73,400 more employees, $530 million more in storage and maintenance facilities, and an additional $330 million in subsidies.

The interaction between the energy shortage and transportation is briefly summarized below.

1) There is and will be an energy shortage which will be critical for at least 5-15 years.

2) Lead times for developing alternative energy sources or increasing production of existing ones imply a continuing dependence on petroleum products.

3) Domestic petroleum reserves are rapidly being depleted and may be exhausted shortly after the

turn of the century, causing an increasing dependence on foreign oil.

4) Transportation is 96% dependent on petroleum and directly consumes over half the petroleum used in this country. There is no chance of a significant decrease in petroleum dependency in the near future.

5) With respect to total energy, the automobile alone accounts for 21% of our national energy budget.

6) While diversion to mass transit conceptually offers considerable savings in petroleum used by transportation, existing systems cannot accommodate a large modal change.

Immediate potential for fuel savings, then, appears to be somewhat confined to operational strategies, such as re-timing traffic control devices in urban areas (especially older ones) to minimize fuel consumption. One study indicated that for one particular 60-intersection system, a fuel savings of 19% could be achieved while reducing delay, increasing average speed, and reducing the number of stops [3]. Claffey's data [13] indicate that at 2 stops per mile, 56% more fuel is required than if a steady speed of 40 miles per hour is maintained.

From a planning standpoint, the need for policies and plans to minimize transportation energy requirements but still maintain mobility has been expressed. These plans and policies should be based upon a careful appraisal of the energy efficiencies of alternative passenger transportation modes, in terms of both general and specific usage [3]. Blake and Cook [7] include the following in a list of needed energy-related research:

1) Planning and construction of transportation systems that minimize energy requirements,

2) Redefinition of transportation "needs" to take energy issues into consideration,

3) Short- and long-term strategies and processes for including energy in the transporation planning process.

Hannon [14] suggests approaching public and private economic development decisions - both operating and capital expenditure - in terms of energy as well as dollars. It is conceivable that such a measure may in the future be required by law, perhaps in the form of an "energy impact statement" similar to the environmental impact statement which became required just a few years ago.

Current practice in quantitative comparison of alternative transportation projects is to use measures of merit based on monetary units, e.g., benefit/cost ratio. The relationship between energy and dollars varies greatly depending on the form of energy being considered. For example, in 1972 the costs of other energy forms relative to coal (relative cost of 1.0) were natual gas (1.2), electricity (11.6), and gasoline (5.8) [4]. Hence, there is no direct relationship between energy and money where more than one form of energy is directly or indirectly involved. There is no mechanism in the transportation decision-making process whereby energy is properly considered. The primary purpose of this dissertation is to formulate a methodology for comparing proposed transportation system alternatives on a net energy basis. The

technique is demonstrated for a particular system which includes two passenger transportation modes - automobile and bus.

Organization

The figure of merit to be used in the energy-based methodology is established and its applications are discussed in Chapter II. Chapter III quantifies (in terms of net energy) the factors for use in establishing system construction and equipment costs; and factors involving system operation and maintenance are presented in Chapter IV. System-user energy costs are developed in Chapter V. The methodology is demonstrated in Chapter VI for an actual express bus-on-freeway project in Miami, Florida. Chapter VII contains conclusions and recommendations for additional related research.

CHAPTER II

CRITERION SELECTION AND APPLICATION

The decision-making process for proposed highway transportation projects presently involves the results of two types of analysis: 1) the cost-benefit analysis, involving priceable quantities, and 2) the effectiveness analysis of quantities which are not priceable. Winfrey and Zellner [15] use the word "economics" in a broad concept of wealth including the production, distribution, exchange and consumption of resources. In this sense, economic analysis is interpreted to include both areas of study.

Basically, cost-benefit analysis considers the highway and its users, while effectiveness analysis includes "community" or non-user consequences such as social and environmental effects. Final decisions concerning proposed projects are usually made after weighing results of both types of analysis. In the past, this has been considered consistent with the principle followed in public works projects that all consequences, to whomsoever they may accrue, are to be considered. The fundamental premise of this dissertation is that because of the shortage of energy resources, energy use per se should be considered separately

in the transportation decision-making process. An energy-based method of analysis would then form a third area to be considered in the overall economic analysis procedure. Such an analysis, based on net energy, is logically an economic analysis because of the production, distribution, and consumption of energy resources involved. Energy is a priceable quantity in the sense that measurable amounts of it in one or more of its forms are required to accomplish such tasks as the manufacture and operation of motor vehicles and the construction and maintenance of highways. The concern over energy consumption by the highway and its users and the priceable nature of energy imply at least a conceptual relationship between an energy-based method and cost-benefit analysis. The primary energy unit used throughout this dissertation is the British Thermal Unit (BTU). Cost-benefit analysis is sometimes referred to as engineering economy analysis because analysis for economy is most often applied to proposals in which engineering is at least partially involved. The end objective for such analyses for economy is conservation of resources [16]. In performing engineering economy analyses, the engineer has the responsibility of designating that choice of alternatives which will perform the desired service with the greatest economy consistent with safety, service, and function. This should be accomplished through comparison of alternatives based on their differences rather than their respective magnitudes [16,17].

Qualities for Criterion

In classical cost-benefit analysis, one of several dollar-based criteria is used to establish ranking of desirability between alternative project proposals. Selection of the criterion used may depend on the type of project being considered (economic evaluation or project formulation), the background or preference of the decision maker, or both. Properties considered desirable for criteria to be used in the energy-based method are identified and discussed below.

1) Comparability between alternatives - the criterion should directly provide a ranking of compared alternatives, establishing both the desirability of one over the other and some measure of the relative difference between them.

2) Commensurability - in comparing alternatives, consequences should be expressed in numbers and the same units should apply to all the numbers.

3) Evaluation/formulation application - the criterion should be applicable to either project evaluation or project formulation. Evaluation is taken to imply an economic choice between mutually exclusive alternatives not necessarily involving the same level of service; formulation is considered to apply to details of design (materials, shapes, etc.) involving the same level of service. It is to be noted that the energy-based method is intended primarily to be used in project evaluation.

4) Inclusiveness - all net energy consumption caused by the system should be considered. This is taken to include that consumed in construction, operation, and maintenance of both motor vehicles and the roadway.

5) Understandability - the criterion should be easily understood by public officials. Winfrey [16] states that in classical analyses, rate methods are better understood than either annual or lump sum values.

6) Priority determination - it is desirable that the criterion be useful in aiding public officials and planners in establishment of project priorities and construction schedules.

Single proposal profitability, of great importance to business and industrial applications, is omitted from the list of desirable qualities for criteria. The reason for the omission is twofold: 1) in the classical sense, there must be an income from the alternative which is nearly always absent in highway projects, and 2) the only type of project that would have an energy "income" would be the energy resource extraction/production process, i.e., there can be no energy "income" from transporation projects.

It is not to be implied that the preceding list of qualities is complete or that any of the qualities listed are of equal merit. It is intended only as a guide for evaluation of candidate criteria.

Candidate Criteria

Criteria considered for use in the energy-based methodology are adapted from those used in classical engineering economy as applied to highways and from those used or proposed for energy efficiency analysis. Candidate criteria in their traditional sense and the general manner in which they may be converted to energy-based transportation analyses are discussed in the following paragraphs.

The Engineering Economy Methods

Conversion of six classical engineering economy methods to an energy basis is performed with retention of the

original format. The reason for so doing is to eliminate any possible misunderstanding between the makeup of a given dollar-based and energy-based criterion, i.e., a user familiar with a given dollar-based criterion should readily and accurately be able to relate to the equivalent energy-based criterion. There is one axiom used in all conversions of engineering economy criteria from a dollar basis to an energy basis: while the dollar has a time value, energy does not, i.e., there is no vestcharge or interest rate associated with energy. The following mnemonic symbols are used:

B/C	Benefit/cost ratio
CR	Capital recovery factor
EUAC	Equivalent uniform annual cost
EUANR	Equivalent uniform annual net return
I	Investment cost (or its equivalent) at time zero in dollars (classical) or BTU (energy)
i	Vestcharge or interest rate (0 for energy)
K	Uniform annual expense of administration, operation, and maintenance in dollars per year (classical) or BTU per year (energy)
n	Analysis period in years
NPV	Net present value
PW	Present worth factor
PWOC	Present worth of costs
R	Gross annual revenue or income (0 for energy)
ROR	Rate of return
SF	Sinking-fund factor

SPW	Series present worth factor
T	Terminal value at end of analysis period
U	Uniform annual road user costs in dollars per year (classical) or BTU per year (energy)
B and P	Subscripts designating base and challenger alternatives, respectively.

It is possible to use only four economic factors or multipliers in expressing the six criteria which are taken from engineering economy. These factors are discussed and converted to their energy equivalent below.

1) Capital recovery factor - the quantity which when multiplied by a present sum will provide exactly an n-year uniform annuity.

   Expressed mathematically

$$(CR,i,n) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

   To convert this to an energy basis, a substitution of i=o is made. As this result is indeterminate, L'Hospital's rule must be applied.

$$(CR,o,n) = \lim_{i \to o} \frac{\frac{d}{di}[i(1+i)^n]}{\frac{d}{di}[(1+i)^n - 1]}$$

$$(CR,o,n) = \lim_{i \to o} \frac{(1+i)^n + in(1+i)^{n-1}}{n(1+i)^{n-1}}$$

$$(CR,o,n) = \frac{1 + o}{n}$$

$$(CR,o,n) = \frac{1}{n}$$

2) Present worth factor - the quantity, which when multiplied by an amount to be withdrawn n years in the future, provides the equivalent value at time zero. The mathematical expression for the present worth factor is

$$(PW,i,n) = \frac{1}{(1+i)^n}$$

Converting this to an energy basis,

$$(PW,o,n) = \frac{1}{(1+o)^n}$$

$$(PW,o,n) = 1$$

3) Sinking-fund factor - the quantity which, when multiplied by an amount to be accumulated n years in the future, will provide the annual sum that must be deposited to obtain that future amount.

Mathematically

$$(SF,i,n) = \frac{i}{(1+i)^n - 1}$$

Conversion to an energy basis again requires

L'Hospital's rule.

$$(SF,o,n) = \lim_{i \to o} \frac{\frac{d}{di}(i)}{\frac{d}{di}[(1+i)^n - 1]}$$

$$(SF,o,n) = \lim_{i \to o} \frac{1}{n(1+i)^{n-1}}$$

$$(SF,o,n) = \frac{1}{n}$$

4) Series present worth factor - simply the inverse of the capital recovery factor.

Mathematically

$$(SPW,i,n) = \frac{(1+i)^n - 1}{i(1+i)^n}$$

For energy

$(SPW,o,n) = n$

These four factors, while representing only a part of those available for economic analysis, are sufficient for use in describing at least one general form of the criteria used in engineering economy. Six of these criteria are discussed in the following items

Equivalent uniform annual cost (EUAC)

In the equivalent uniform annual cost method, all estimated future net cash flows for highway capital investment, maintenance, and operation and motor vehicle expenses are reduced to a single uniform annual sum that is equivalent to all disbursements over the analysis period. The method is applied to alternatives individually and seeks to identify the alternative with the lowest total cost of highway transportation. The solution can be directly converted to present worth of costs by multiplying by the series present worth factor. One form of the equivalent uniform annual cost given in References 15 and 16 is

$$EUAC = -I(CR,i,n) + T(SF,i,n) - K - U$$

The solution will be negative, indicating cash outflow, and that alternative having the least outflow is the cost desirable. The method has long been used in highway as well as industrial applications. However, the result implies only cost magnitudes and is therefore not applicable to comparison of mutually exclusive alternatives or in comparison of independent alternatives under unequal levels of

service [15,16,18]. Thus the common application is limited to project formulation where design features are considered that in no way affect the running cost of motor vehicles on the highway. Winfrey [16] states that the method cannot be used to measure the desirability of proposals; it can only identify the differences between proposals. Thus the method cannot even be used to evaluate the desirability of an existing facility, and if an existing facility is not economically desirable, then usually there is nothing to be gained by improving it or replacing it. The mathematical expression for equivalent uniform annual cost on an energy basis is

$$EUAC = -I(CR,o,n) + T(SF,o,n) - K - U$$

Making the proper substitutions

$$EUAC = -I(\frac{1}{n}) + T(\frac{1}{n}) - K - U$$

This appears to be the average annual energy cost (or equivalent annual consumption) of the system in BTU per year over the analysis period. However, it is considered that the true terminal energy value is zero. If n is some value other than the lifetime of the system, the terminal value could be interpreted as being an energy value which represents the unused part of facility life. For simplifying purposes, analysis period and facility lifetime will be assumed identical and terminal value will be considered zero in the remainder of this section. Finally, energy-based equivalent uniform annual cost becomes

$$EUAC = -I(\frac{1}{n}) - K - U$$

Present worth of costs (PWOC)

The present worth of costs method reduces all highway and highway user costs to one equivalent sum at zero time. This sum plus interest earnings would exactly finance all highway disbursements and road-user expenses through the analysis period. The equation for present worth of costs as expressed in References 15 and 16 is

$$PWOC = -I + T(PW,i,n) - K(SPW,i,n) - U(SPW,i,n)$$

The same comments previously made about the equivalent uniform annual cost method apply here because the two methods are directly related by the capital recovery factor. The only advantage that one of these forms has over the other is that public officials do not understand the present worth of costs method as well as they do the equivalent uniform annual cost method. The form for present worth of costs on an energy basis is

$$PWOC = - I + T(PW,o,n) - K(SPW,o,n) - U(SPW,o,n)$$

Substitution of the energy-based factors yields

$$PWOC = - I + T - nK - nU$$

This would be the total energy cost of the system over the analysis period if terminal value existed. Under the previously stated assumption for this section (only), the facility lifetime and the analysis period are identical. Therefore, there is no energy-based terminal value. Finally,

$$PWOC = - I - nK - nU$$

Equivalent uniform annual net return (EUANR)

The equivalent uniform annual net return method is similar to the equivalent uniform annual cost method with an income factor. As the method primarily applies to private business situations involving cash income and outflow relative to the business, road-user costs are not considered, i.e., the only cash flows considered in highway practice would be those directly associated with the sponsoring agency. The mathematical relationship may be expressed by

$$EUANR = - I(CR,i,n) + T(SF,i,n) - K + R$$

The answer indicates the amount by which the positive equivalent uniform annual income exceeds (or is less than) the negative equivalent uniform annual highway cost. The alternative having the largest positive equivalent uniform annual net return is considered best. In using the method, the vestcharge rate used is the minimum attractive rate of return [16]. Therefore the equivalent uniform annual net return is a direct measure of economic desirability. The method is equally applicable to project formulation or economic evaluation, and level of service is not a factor since the method measures income against highway costs only. The income factor limits application of the method to those proposals that have a dollar-priced income, a situation usually absent from highway analyses. Because of this limitation, Winfrey and Zellner [16] do not consider the method useful. The solution may be directly converted

to net present value by multiplying by the series present worth factor.

The general expression for energy-based equivalent uniform annual net return is

$$EUANR = - I(CR,o,n) + T(SF,o,n) - K + R$$

As stated earlier in this chapter, there is no energy income associated with transportation systems. Therefore, there is no net return when this method is applied on an energy basis, and, from a terminology standpoint, the approach does not exist because of this lack of a return quantity. Mathematically, the energy application, if carried through, reverts to the equivalent uniform annual cost method with road-user costs excluded. This method is not considered to be applicable to the energy-based methodology.

Net present value (NPV)

The net present value method gives the difference in the present worths of outward cash flows and inward flows of incomes. Because of the relationship previously described between the equivalent uniform annual net return method and the net present value method, the assessment of this method is similar. The energy-based application would, as might be expected, give the same results as the present worth of costs method if road-user costs were excluded. This method, like the equivalent uniform annual net return method, is considered inapplicable for energy analyses and will not be pursued further. The classical economic net present value

relationship is expressed below for completeness.

$$NPV = - I + T(PW,i,n) - K(SPW,i,n) + R(SPW,i,n)$$

Rate of return (ROR)

The purpose of the rate of return method is to identify the interest or vestcharge rate that equalizes the discounted value of the negative costs and positive benefits over the analysis period. The answer is in percentage form (rate of return on the original investment) and the method is applied to alternatives in pairs, i.e., challenger and base alternatives. The relationship, which must be solved iteratively, is given as

$$0 = - (I_P - I_B)(CR,i,n) + (T_P - T_B)(SF,i,n) - (U_P - U_B) - (K_P - K_B)$$

Unfortunately, in rare cases there may be either no answer or two rates of return that will satisfy this expression. Winfrey and Zellner [15] imply that the latter occurrence is unlikely in the highway field although it may be possible in cases involving stage construction. The method is applicable to both project formulation and economic evaluation. Winfrey [16] states that this criterion is more meaningful than the other methods to most decision makers because of their familiarity with rates of return on other types of investments. Level of service is not a restriction on the method; in fact an advantage of the method is that it reduces alternatives to a common base (rate of return) for comparison.

This method in its classical form cannot be applied to energy analysis because of the zero vestcharge rate associated with energy.

Benefit/cost ratio (B/C)

The benefit/cost ratio method, simply stated, expresses the ratio of net benefits to net costs either on a present worth basis or on an equivalent uniform annual basis. Any alternative with a benefit/cost ratio greater than 1.0 is economically feasible. Net benefits or net gains are usually measured in terms of differences between two alternatives, although the method can be applied to a single alternative which generates its own benefits. The method is applicable to either economic evaluation or project formulation. A typical equivalent uniform annual form for benefit/cost ratio is

$$B/C = \frac{-\ (U_P - U_B)\ -\ (K_P - K_B)}{-\ (I_P - I_B)(CR,i,n)\ +\ (T_P - T_B)(SF,i,n)}$$

Application of the method to a set of alternatives requires an incremental analysis. While comparison of all alternatives in the set to a common base will define the profitability of each with respect to that common base, the answers thus generated may not be used to directly compare the alternatives in the set with each other. The proper analytical procedure is to sequentially compare all alternatives to what amounts to a variable base. In each comparison, the "winner" becomes (or remains, as the case may be) the base alternative for the next comparison. This procedure is depicted in Figure 1. Of the six alternatives, A through F, it is desired to determine that which is most preferable. First, B is considered the challenger alternative

and A is considered to be the base. Alternative B is found to be better than A (B/C is greater than 1.0) and becomes the base alternative for comparison with alternative C. In this comparison, B was again found to be the preferred alternative (B/C is less than 1.0) and continues to be the base alternative in the next comparison. The procedure is continued for all six alternatives, with alternative E being the one ultimately being found the most desirable.

COMPARISON	CHALLENGER	BASE	WINNER
B with A	B	A	B
C with B	C	B	B
D with B	D	B	B
E with B	E	B	E
F with E	F	E	E

Figure 1 Sample Benefit/Cost Analysis Procedure

The method is found mainly in public works and has been used almost exclusively in the highway field since 1952 [16]. Winfrey and Zellner [15] state that the method has no particular objectionable features and is reliable. While gains or benefits are expressed as a rate, the abstractness of the final ratio is more difficult to interpret than is a rate of return [16]. Because the method is a rate method, level of service is not a factor in its use.

In practice, inconsistencies can exist in application of the benefit/cost ratio. These are due primarily to differing opinions as to classification of benefits and costs. For example, it could be stated that terminal income is as logically a benefit as is any reduction in road-user cost. However, according to Winfrey [16], terminal value is a deduction from capital cost and to consider it as otherwise leads to overstating capital costs on which the degree of profitability is measured. While the literature does not raise this question (of placing terminal value in the numerator), there are differences of opinion as to the positioning of operating and maintenance costs [15-17,19,20]. Wohl and Martin [20] consider this to be a deficiency in the method. Some feel that the benefit/cost ratio should be formed by benefits to the public (road user) in the numerator and costs paid by the government or highway agency in the denominator. This application places the costs of operation, maintenance, and administration in the denominator. Winfrey [16] is of the opinion that these costs properly belong in the numerator as a negative road-user benefit. Justification for this opinion is summarized below.

1) The real base of outflow of cash is the investment. The objective of the analysis is to determine whether or not benefits exceed this. Thus, putting operations, maintenance, and administration costs in the denominator is "illogical and conceptually unsound."

2) Placing these costs in the numerator is consistent with cost accounting procedures, e.g., operating expenses are deducted from income before gross profits are stated.

3) The net present value and rate of return methods also treat these costs as a deduction from income.

It is to be noted that regardless of the positioning used, the result of the benefit/cost analysis procedure will always provide the same qualitative solution. Only the magnitude of the ratio is affected by the position of this group of annual highway costs. The mathematical form given earlier is the only one included in a recent publication of the American Association of State Highway and Transportation Officials [18] and will be the general form used in this dissertation. The general energy-based equivalent of this form is given by

$$B/C = \frac{-(U_P - U_B) - (K_P - K_B)}{-(I_P - I_B)(CR,0,n) + (T_P - T_B)(SF,0,n)}$$

or

$$B/C = \frac{-(U_P - U_B) - (K_P - K_B)}{-\frac{1}{n}(I_P - I_B) + \frac{1}{n}(T_P - T_B)}$$

Under the simplifying assumptions of zero terminal value and analysis period/facility lifetime equivalence, this further reduces to

$$B/C = \frac{-(U_P - U_B) - (K_P - K_B)}{-\frac{1}{n}(I_P - I_B)}$$

The sign classification used is the same as that of Winfrey [16]. All relevant terms are expressed as challenger minus base alternatives and the sign convention treats income (as from terminal value) as positive and outflow as negative. The sign of the ratio itself is taken

to be that of the numerator only, i.e., the sign of the denominator is ignored. A negative value of the numerator means that net benefits are negative and the alternative should no longer be considered.

Energy Efficiency Methods

Two concepts of energy efficiency will be assessed as candidate criteria for the energy-based methodology. The first is based on a measure normally used in macroscopic comparisons of various forms of passenger and freight transportation. The second concept is one recently proposed to measure energy utilization.

Energy intensiveness (EI)

Several comparison measures have been used to gauge the relative efficiencies of the various transportation modes. Rice [21] offers an index called energy intensiveness which is the inverse of the product of technical efficiency (e.g., BTU/seat-mile) and load factor (e.g., passenger miles per seat-mile). The units of energy intensiveness are BTU/passenger-mile and BTU/ton-mile for passenger and freight movements, respectively. Energy efficiency can be expressed as the inverse of energy intensiveness; however, the latter form appears to be the more predominant in the literature [4,11,12,22]. Application of the criterion has not in practice been based on net energy. Several other energy efficiency measures which have been used are listed below.

1) Relative efficiency - an index of efficiency in terms of miles/energy unit (e.g., miles/gallon) divised by occupancy, all normalized to a base of 100 which represents an automobile carrying three persons and traveling 14 miles on a gallon of gasoline [5].

2) Specific energy - technical efficiency for passenger movement, i.e., energy consumed per seat-mile [9].

3) Direct energy efficiency - the product of technical efficiency (in terms of energy expressed as equivalent gallons of gasoline) and load factor [3]. The boundaries of the energy system are the gas tank for internal combustion engine powered vehicles and the generating station for electrically powered vehicles.

All of these measures are actually variations of Rice's index [21] but are not further considered since relative efficiency is difficult to interpret quantitatively, specific energy neglects loading, and direct energy efficiency is based on an arbitrary gasoline standard rather than any of the standard energy units.

The primary disadvantage of using energy intensiveness as a criterion for the energy-based methodology is the division into passenger and freight classes. Because of this division, construction and operations, maintenance, and administrative energy costs cannot be properly considered (or allocated) in computation of the two energy intensiveness quantities, e.g., apportionment of maintenance costs to that due to automobile traffic and that due to trucks cannot be performed with any reasonable degree of accuracy. The application of the energy intensiveness parameter then is limited to road-user costs such as fuel and oil consumption, maintenance, parts, etc. This approach is not

generally applicable to project formulation where levels of service are equal.

Energy utility (Y)

One parameter proposed for evaluating energy systems is energy utility [23]. The approach, primarily intended for application in cascaded thermodynamic systems, concerns the total benefit or utilization which may be derived from a given amount of energy entering an energy system. Two quantities are required for determining utility: utilization (y) and availability (A_r). Utilization is defined as the useful work accomplished plus the energy applied. Availability is the product of Carnot Efficiency and the energy input to the system. This represents the maximum energy output possible for a heat engine operating between the same temperature limits with the same energy (heat) input. Utilization may be expressed for thermodynamic systems by

$$Y = W_u + Q_{app} \quad \text{(heat addition processes)}$$

or

$$Y = W_u + Q_{ref} \quad \text{(refrigeration processes)}$$

where

W_u = useful work

Q_{app} = heat applied

Q_{ref} = heat removed.

The mathematical expression for availability is

$$A_r = Q(1 - \frac{T_C}{T_H})$$

where

Q = energy input to the system

T_C, T_H = lower and upper absolute operating temperature limits respectively, of a heat engine.

Finally, utility is expressed as

$$Y = \frac{y}{A_r}$$

Energy used in the various aspects of constructing, maintaining, and operating a transportation system is cascaded. Unfortunately, there is currently no theoretical minimum energy quantity on which to base most of the required analyses, e.g., the method is applicable for power-generating plants and internal combustion engines, but not for the movement of persons or goods. This method, then, is not further considered as a candidate criterion.

Assessment of Candidate Criteria

Of the eight criteria considered for use in the energy-based methodology, four were judged not to be applicable. Compatibility between the remaining four candidates and the six desirable qualities for criteria discussed previously is shown pictorially in Figure 2. While no consideration is given to the degree of achievement of these qualities, it is shown that the benefit/cost ratio is the only criterion that at least partially possesses all the desirable qualities considered. Furthermore, the benefit/cost ratio is the only candidate which is applicable to priority determination and evaluation/formulation

application. For these reasons, the benefit/cost ratio is that criterion recommended, and the remainder of this dissertation is developed under the assumption that it will be used for energy-based analyses of proposed transportation projects. While the separate passenger and freight quantities would likely rule out energy intensiveness as a practical criterion for determining project feasibility, it is conceivable that in some instances the energy-based equivalent uniform annual cost or the present worth of costs approach might be desired as a matter of personal preference. These two criteria use the same general terms as benefit/cost ratio. The material developed in Chapters III, IV, and V is therefore suitable for application with these two methods.

desirable qualities \ candidates	EUAC	PWOC	B/C	EI
1. Comparability between alternatives	X	X	X	
2. Commensurability	X	X	X	
3. Evaluation/formulation application			X	
4. Inclusiveness	X	X	X	
5. Understandability	X		X	X
6. Priority determination			X	

Figure 2 Candidate Criteria/Desirable Quality Compatibility

Application of Benefit/Cost Ratio

Alternatives and Consequences

Winfrey [16] cites two principles used in economic analysis of public investments.

1) All alternatives should be considered.

2) All consequences to whomsoever they may accrue should be considered.

Alternatives to be considered

Consideration of all alternatives includes the do-nothing alternative and abandonment of the existing facility as well as all improvement alternatives. Proposals for highway improvements in which there may be a question of whether or not an existing facility should be abandoned are so infrequent that this alternative is not generally recognized in the normal practice of engineering economy studies [15]. In principle, however, comparison of the abandonment and do-nothing alternatives establishes the desirability of the existing facility. Most often, proposals are based on improvements to the existing facility or addition of another facility which in part serves the same purpose as the existing one. Consideration of all possible alternatives for improvement usually leads to detailed analysis of only a few, because factors such as level of service, cost, and construction difficulties allow some alternatives to be set aside immediately.

Treatment of consequences

From an engineering economy standpoint, consideration

of "all consequences" implies the need of a spatial systems approach. The system boundaries should conceptually extend in space on both sides of the proposed improvement to a point where the improvement has no influence on traffic operation or travel demand. In the analysis of mutually exclusive alternatives, demand may come from traffic diverted from other facilities and traffic generated by (and because of) the new facility as well as that traffic considered to be existing on the current facility. Operationally, a new facility may cause an increase in congestion on streets approaching it, and because of diversion, traffic on existing parallel facilities may be greatly benefited. Similar effects may be expected for new traffic control strategies. Obviously, common factors of equal magnitude may be neglected when comparing alternatives.

The proper procedure for treating generated traffic is not absolutely defined, as this traffic did not previously exist and therefore has no base on which to compute its net benefit. Of course, this traffic is benefited by the new facility because it is demonstrating a preference for the facility in lieu of whatever activity is would otherwise have supported. Thus, Winfrey [16] concludes that no serious error can result in treating generated traffic in the same manner as existing traffic even though this approach <u>may</u> overstate feasibility.

Analysis Period

Selection of an analysis period is constrained by facility lifetime(s) and the time span for which reliable estimates of demand may be made. The analysis period used should be no larger than the smaller of the two values. Reasonable forecasts of demand are usually limited to a 15- to 25-year period [18]. Since high type surfaces such as portland cement concrete and bituminous concrete have average lives of 27 and 20 years, respectively [19], the accuracy of the forecast period is usually the controlling factor in selection of the analysis period. Because of the uncertainty of the time required for development of new propulsive sources, the analysis period perhaps should be no greater than 15 years.

Final General Form of Energy-based Benefit/Cost Ratio

For ease of understanding in comparing the various candidate criteria for determining project feasibility, a simplifying assumption was made equating facility lifetime and analysis period. This is, of course, not generally true. In practice using the classical method, terminal value, if not the same between two alternatives, is taken to represent the unused portion of the capital investment. A final form of benefit/cost ratio as related to highway improvements is developed under the assumption that energy-based terminal value of a facility decreases linearly with time to zero at the end of facility life.

Let

I = energy-based investment cost of the facility in BTU

L = facility lifetime in years

n = analysis period in years

T = energy-based terminal value at the end of the analysis period in BTU.

Then we may write the general expression for terminal value

$$T = (1 - \frac{n}{L})I$$

Recalling the general expression for energy-based benefit/cost ratio

$$B/C = \frac{-(U_P - U_B) - (K_P - K_B)}{-\frac{1}{n}(I_P - I_B) + \frac{1}{n}(T_P - T_B)}$$

Substituting the expression for terminal value

$$B/C = \frac{-(U_P - U_B) - (K_P - K_B)}{-\frac{1}{n}(I_P - I_B) + \frac{1}{n}[(1 - \frac{n}{L_P})I_P - (1 - \frac{n}{L_B})I_B]}$$

or

$$B/C = \frac{-(U_P - U_B) - (K_P - K_B)}{-(\frac{1}{L_P}I_P - \frac{1}{L_B}I_B)}$$

Thus energy-based benefit/cost ratio is the ratio of equivalent uniform annual benefits over the n-year analysis period and average lifetime-based investment costs. A special case arises when the base alternative is the do-nothing alternative: there is no investment for the base. The benefit/cost ratio is then expressed as

$$B/C = \frac{-(U_P - U_B) - (K_P - K_B)}{-\frac{I_P}{L_P}}$$

This is the annual net benefit divided by the effective annual cost. The net annual gain is the difference between benefits and costs

$$\text{Annual Gain} = -\frac{I_P}{L_P} - (U_P - U_B) - (K_P - K_B)$$

This can be placed on a rate basis by dividing the annual gain by the effective annual cost. This is an energy-based rate of return (EROR)

$$\text{EROR} = \frac{-\frac{I_P}{L_P} - (U_P - U_B) - (K_P - K_B)}{\frac{I_P}{L_P}}$$

or when proper signing is chosen for benefit/cost ratio

$$\text{EROR} = B/C - 1$$

This rate of return is not the same as that used in classical cost-benefit analysis. It does, however, define the energy gain per unit of energy investment during the analysis period. Any rate greater than zero would indicate a desirable alternative. It is emphasized that this approach is valid only when the base alternative is the do-nothing alternative.

The analysis procedure should be to first compare each alternative with the present facility if such exists to determine those which are feasible from an energy standpoint. Energy-based rate of return as defined in this section may then be obtained by inspection. Once this is accomplished, stepwise comparison of alternatives can

begin. The necessity of comparing each "do-something" alternative with the existing facility stems from the fact that final decisions are based on classical cost-benefit analysis and effectiveness analysis also.

CHAPTER III

CONSTRUCTION AND EQUIPMENT INVESTMENT COSTS

The production and sale of a commodity (or the provision of a service) has an associated energy "cost." This energy cost consists of direct energy supplied from an energy producer to the manufacturer and indirect energy inputs to components or processes along the overall production chain. For example, the automobile industry directly consumes only about 7% of the energy needed to make a car. The remaining 93% is used indirectly in mining of ore, manufacture of steel, etc.

The purposes of this chapter are to 1) describe a technique by which total energy use may be estimated, and 2) define unit energy requirements for items normally associated with construction and equipment investments for transportation systems. The technique described also applies to maintenance, operations, and road-user energy costs.

Energy Coefficient Methodology

The basic vehicle for estimating direct and indirect energy requirements for services and production and sales of goods is the economic input-output method of Wassily Leontief.

An analogous energy-based technique is applied to energy producers and then coupled with the economic input-output procedure of Leontief to obtain unit energy costs.

Input-Output Analysis

Input-Output (I/O) analysis is a technique which enables one to make predictions of the interindustry economic effects created by a change in final demand in one or more industries. A knowledge of yearly interindustry and intraindustry sales and final demand sales for each industry is required. These quantities are usually stated in terms of producers' prices and, because of this, total input to an industry is equivalent to its total output. This "state" of an economy may be illustrated by the highly simplified transactions (or I/O) table shown in Table 1 for a three-industry economy. The transactions table consists of the processing sector, the final demand sector, and the payments sector. The processing sector contains the industries (or sectors of the economy) producing goods and services such as agriculture, manufacturing, utilities, communications, etc. The payments sector represents effective industry inputs and may include the broad categories of gross inventory depletion, imports, depreciation allowances, payments to government, and households (in the form of wages). Categories belonging to the final demand sector are gross inventory accumulation, exports to foreign countries, government purchases, gross private capital

formulation, and households. It is noted that because total outlays must equal total inputs for the economy as a whole, the sum of final demand values must be equivalent to the sum of total payments.

Table 1 Hypothetical Transactions Table

Outputs / Inputs	Processing Sector			Total Final Demand	Total Output
	Industry A	Industry B	Industry C		
Industry A	2	2	2	2	8
Industry B	4	0	0	12	16
Industry C	0	0	0	2	2
Total Payments	2	14	0	0	16
Total Input	8	16	2	16	42

In examining the set of transactions for industry A, we see that its outputs are such that it provides 2 units to itself, 2 units each to industries B and C, and 2 units to final demand for a total output of 8 units. To obtain this output, industry A uses 2 units of its own output, 4 units from industry B, and 2 units from the payments sector. Another industry, such as industry C, may not return any of its output to industries, i.e., all of its output may go to the demand sector.

Suppose that there is an increase of 1 unit in final demand for the output of industry A. Then the input to industry A from other industries and from the payments

sector must increase by a total of 1 unit. According to the transactions table, some of this must come from industry B and some from industry A in order to produce A's product. Thus the output of industry B is increased and the output of industry A must be increased still further. This implies an iterative procedure for determining the overall effects of a change in final demand. Determination of these effects is the objective of I/O analysis.

The economy may be considered to consist of n+1 sectors. Of these, the final demand sector is autonomous. The other n sectors are not, and, with suitable assumptions, their structural interrelationships can be established. I/O theory assumes that the inputs of each of the nonautonomous sectors to a given sector are linearly related to the total output of the given sector. Define the following:

X_i = the total output of sector i ($)

x_{ij} = the interindustry (or intraindustry) output of industry i to industry j ($)

y_i = final demand of industry i ($).

Under the stated assumption of linearity, interindustry output may be written

$$x_{ij} = a_{ij}X_j \qquad (1)$$

where a_{ij} is a constant. Total output of industry i is by definition

$$X_i = \sum_{j=1}^{n} x_{ij} + Y_i$$

Substituting the linear relationship

$$X_i = \sum_{j=1}^{n} a_{ij}X_j + Y_i$$

or, in matrix form

$$X = AX + Y$$

The preferred final form is

$$X = (I - A)^{-1}Y \qquad (2)$$

where I is the identity matrix. The jx1 X matrix is the processing sector matrix from the transactions table. The A matrix is called the table (matrix) of direct coefficients and the jxi $(I - A)^{-1}$ matrix is the table of total (direct plus indirect) requirements. A value in the matrix of total coefficients is the dollar output of sector i required for the economy to deliver a dollar's worth of final demand from sector j.

This particular I/O model is referred to as a static, open model where the coefficients are assumed to be constant over time and the final demand vector (only) consists of exogenous variables. A more complete theoretical approach to I/O theory is given by Henderson and Quandt [24], while Miernyk [25] presents a nontechnical practical approach to I/O analysis which includes dynamic modeling. The static, open model presented in the previous paragraph, however, is that which is currently used as a basis for determining total energy coefficients.

The Total Energy Coefficient

Analysis of energy flows differs from that of I/O analysis in two respects. First, energy output of an energy producer is governed by thermodynamics rather than economics, i.e., energy output can be thought of as the product of energy input and process efficiency. Second, end-user industrial sectors and also the final demand sector do not necessarily pay the same price for energy. For example, in 1963 the average commercial price for electricity was 2.29 cents per kilowatt-hour. Industrial customers averaged 0.90 cents per kilowatt-hour, and the primary aluminum industry paid only 0.33 cents per kilowatt-hour [26].

The output for all energy-producing sectors of the economy (both primary and secondary) may be written as follows:

$$E_i = \sum_{k=1}^{p} E_{ik} + \sum_{j=p+1}^{n} E_{ij} + D_i \tag{3}$$

where D_i = final demand for energy from energy-producing sector i (BTU)

E_i = total energy output of energy-producing sector i (BTU)

E_{ij} = total energy input from energy producer i to industrial energy end-user j (BTU)

E_{ik} = total energy input from energy producer i to energy producer k (BTU)

p = total number of primary and secondary energy producers in the economy.

Now define the following:

$$D_i' = \sum_{j=p+1}^{n} E_{ij} + D_i \tag{4}$$

Substitution into Equation (3) gives

$$E_i = \sum_{k=1}^{p} E_{ik} + D_i' \tag{5}$$

This may be thought of in the same sense as a transactions table, with D_i' being a psuedo-final demand vector. This approach is permissible because the industrial end-users by definition provide no energy back to the energy producers.

As previously stated, the energy output of an energy producer is related to the efficiency of the process and energy inputs. It is assumed that the energy input from one sector to another sector divided by the energy output of the second sector is a constant, mathematically expressed as

$$\frac{E_{ik}}{E_k} = q_{ik} = \text{constant}$$

Substitution into Equation (5)

$$E_i = \sum_{k=1}^{p} q_{ik}E_k + D_i'$$

Rearrangement and use of matrix notation gives

$$E = (I - Q)^{-1}D'$$

or

$$E = CD' \tag{6}$$

where

$$C = (I - Q)^{-1}$$

An element of the pxp C matrix represents the energy required from energy producer k to deliver 1 BTU to pseudo demand sector i. Let

p_i = the price of energy from producer i sold to final demand Y_i (\$/BTU)

p_{ij} = the price of energy from producer i sold to nonenergy-producing sector j (\$/BTU).

Then

$$E_{ij} = \frac{x_{ij}}{p_{ij}}$$

and

$$D_i = \frac{1}{p_i} Y_i$$

Substitution into Equation (4) gives

$$D_i' = \sum_{j=p+1}^{n} \frac{x_{ij}}{p_{ij}} + \frac{1}{p_i} Y_i$$

From the I/O theory assumption

$$x_{ij} = a_{ij} X_j$$

Therefore

$$D_i' = \sum_{j=p+1}^{n} \frac{a_{ij}}{p_{ij}} X_j + \frac{1}{p_i} Y_i$$

Define

$$r_{ij} = \frac{a_{ij}}{p_{ij}}$$

Then

$$D_i' = \sum_{j=p+1}^{n} r_{ij} X_j + \frac{1}{p_i} Y_i$$

This may be extended to the general final demand vector by making the following definitions:

$$r_{ij} = \frac{a_{ij}}{p_{ij}} \text{ for } j=p+1 \text{ to } n$$

$$= 0 \text{ otherwise}$$

$$s_{ij} = \frac{1}{p_i} \text{ for } i=j \text{ up to } i=j=p$$

$$= 0 \text{ otherwise.}$$

Thus

$$D_i' = \sum_{j=1}^{n} r_{ij}X_j + \sum_{j=1}^{n} s_{ij}Y_j$$

Substituting Equation (2) and using matrix notation

$$D_i = [R(I - A)^{-1} + S]Y$$

Finally, substitution into Equation (6) gives

$$E = C[R(I - A)^{-1} + S]Y$$

We may further define the kxj matrix of total energy coefficients T

$$T = C[R(I - A)^{-1} + S]$$

such that

$$E = TY \tag{7}$$

Data Base

The primary data source for energy-based I/O analysis is the set of economic I/O tables generated by the Bureau of Economic Analysis (B.E.A.) [27]. These tables are based on census data for a 367-sector U.S. economy as it existed in 1963. Herendeen [26] has used this set of data as a basis for generating energy coefficients for a 362-sector economy. These tables are based on the following five energy-producing sectors:

1) Coal

2) Crude oil and gas extraction

3) Refined petroleum

4) Electric utilities

5) Gas utilities.

The total primary energy per dollar of final demand of sector j is obtained by summing the coal and crude oil and gas required per dollar of final demand of j. Herendeen modifies this quantity to account for hydro- and nuclear power which combined accounted for slightly over 18% of the energy used in the U.S. in 1963.

A question arises as to the time variation of the total energy coefficients. The accuracy of the coefficients even in 1963 is limited by the accuracy of the data from which they are derived and the degree of disaggregation of the U.S. economy. Over a period of time, the amount of energy per dollar of final demand for a given product may change because of 1) the changing value of the dollar itself, 2) changes in energy efficiency in the manufacturing process for the item, and 3) changes in any components which make up the item, their materials, or their manufacturing energy efficiencies. Herendeen suggests, as a first-order approximation, that the time variation of the total energy coefficients be accounted for by multiplying the total energy coefficient by the ratio of total national primary energy use per gross national product for the year in question to the total national primary energy

use per gross national product for 1963; e.g., for 1970, the total energy coefficients computed by Herendeen would be multiplied by 0.83 [26]. While corrections of this type are used in this dissertation, it is felt that the major source of the time variation for most items is caused by the changing value of the dollar. For instance, over the past several years, one might expect the change in steel prices to have a much greater effect on the total energy coefficient for a steel I-beam than any change in the energy efficiency of the mining/manufacturing process. For this reason, attempts are made in later sections to estimate energy usage in terms of physical units rather than dollar units, e.g., BTU per barrel of cement or BTU per gallon of gasoline.

Some insight into the accuracy of the overall process for energy estimation may be gained by examining the results of three energy approximations for the manufacture of an item composed of numerous materials and components, and one whose makeup varies from year to year - the automobile. Herendeen estimates the energy required to manufacture an automobile in 1963 to be 132×10^6 BTU per car [26]. Application of the method to 1970 manufacturing and wholesale price data results in a value of 129×10^6 BTU per car manufactured in 1970. Berry and Fels [28] performed an analysis for the manufacture of a 1967 automobile using somewhat detailed chemical analyses of energy and materials throughout the overall mining/manufacturing process.

This approach, considerably different from and much more laborious than the I/O approach, resulted in a value of $126x10^6$ BTU per car. Had Berry and Fels included tires in their study, their results would have coincided even more closely with the I/O-based studies. The results of these analyses tend to 1) quantitatively verify the accuracy of the approach, and 2) demonstrate the slight time variation of physical unit-based energy of manufacturing. Between 1963 and 1970 the energy required to manufacture a car varied by only 2.3%, while the wholesale price rose by 17.1%.

Roadway Construction and Equipment Energy

The total cost of a roadway includes right-of-way, engineering, and construction, each of which has an associated energy cost. This section includes an analysis of energy contributors, an approximate method of estimating the total energy cost of a roadway, and a table of estimated energy requirements for new highway construction in each of the fifty states for the Federal-aid Primary System.

Energy Contributors

One of the sectors of the economy for which national energy data are provided is titled "New construction, highways." However, the differences in construction requirements and right-of-way costs for various classes of roadways and locations render use of a single total primary energy coefficient inadequate for specific analyses.

More useful information is gained by examining the direct dollar coefficients for industries providing inputs into highway construction. There are 85 sectors of the economy which provide these inputs [27]. These direct inputs comprised about 57.6% of total highway construction dollar costs in 1963, with the remaining 42.4% coming from the "value added" category (wages, profits, etc.). As an approximation (for ultimately developing a user-oriented model), it will be assumed that energy expended under the "New construction, highways" category may be represented by the sum of total final demand primary energies for each of these contributing items and a correction factor to account for the difference in energy required for final demand of these items and energy required for "New construction, highways." It should be noted that "value added" is considered to be a dollar quantity only, and one which has no energy value. By using the dollar percentages for each of the 85 items making up the direct inputs to the highway construction industry and the total primary BTU per dollar for each, an estimate of the total primary energy for the highway construction industry may be obtained. The result of this computation is 1.0738×10^5 BTU per dollar of final demand for highway construction as opposed to 0.98507×10^5 BTU per dollar of final demand given by Herendeen [26]. This use of component energies, then, overestimates energy use by about 9%. A correction factor of 0.917 is required to account for the difference in energy

required per dollar of final demand and the energy required per dollar of highway construction. It is assumed that this correction applies equally to each of the industrial sectors providing direct inputs to highways.

An evaluation of the relative energy contributions of each of the 85 contributing sectors reveals that only 16 of these sectors account for approximately 93% of the total energy required for highways. These 16 sectors are those wherein each provides 1% or more of the total energy requirement. These sectors and their relative contributions to cost and total energy required are shown in Table 2. It is seen that there may be considerable difference in the contributions of dollars and energy for a given contributing sector. The sectors shown in Table 2 are generally classified as materials, their transportation, their wholesaling, and miscellaneous professional services (e.g., engineering). The other 69 contributing sectors not shown in Table 2 include other materials, transportation costs by other modes, retail trade, real estate, insurance, equipment, etc.

An Energy Model for Highway Construction

The previously defined form of total primary energy coefficients (BTU per dollar) is not generally practical for estimating energy requirements for specific highway construction projects. The reasons follow:

1) Computation of the ratio of total primary national energy use to Gross National Product would be required to update the coefficients timewise.

Table 2 Significant Energy Contributors for New Highway Construction - 1963

Sector title	percent of total cost	percent of total energy
Stone and clay mining and quarrying	3.55	3.12
Miscellaneous chemical products	0.41	1.09
Petroleum refining and related products	3.45	36.86
Paving mixtures and blocks	1.57	6.54
Cement, hydraulic	2.33	9.17
Concrete products, not elsewhere classified	2.56	2.24
Ready-mixed concrete	3.80	5.06
Blast furnace and basic steel products	5.44	13.31
Fabricated structural steel	3.63	4.18
Sheet metal work	1.88	2.01
Miscellaneous metal work	1.34	1.67
Miscellaneous fabricated wire products	1.06	1.42
Railroads and related service	1.40	1.07
Motor freight transportation and warehousing	2.61	2.04
Wholesale trade	4.04	1.25
Miscellaneous professional services	7.24	1.79
TOTAL	46.31	92.82

2) Some construction materials for a given project may be obtained from one or more of several categories, and the exact classification may not be known to the estimator.

3) The values of transportation energy and energy required for sales of each of the contributing materials are generally unknown.

A procedure is developed in this section by which the total energy required for a new highway project may be estimated. The procedure, although a rather crude one, is especially useful in that total energy requirements are predicted from quantities of common construction materials for which statistical usage data are readily available.

First, the contributions of engineering and right-of-way costs are separated from overall project costs; that is, the model is based on construction data. Between 1956 and 1974, an average of 12.4% of total highway project costs involving federal aid went to engineering and right-of-way and the remaining 87.6% was consumed in construction [29]. It is assumed that this percentage is valid for 1963. A sizeable portion of this 12.4% went directly to sellers of right-of-way in the form of land transfer involving no energy. Some of these funds went to industries involved in sales and financing of right-of-way such as real estate, banking, and security and commodity brokers. The remainder of the 12.4% was consumed in engineering costs. All of the industries involved in engineering and right-of-way costs tend to be labor intensive rather than energy intensive. While total dollar and energy contributions for those I/O sectors which play a part in engineering and right-of-way may be identified from the 1963 table of direct I/O coefficients [27], the allocations of these contributions between construction and engineering and right-of-way cannot be made for all items. For example, the advertising

sector likely contributes both to construction and engineering and to right-of-way but by unknown amounts. As an illustration of the proportionately low energy contributions of engineering and right-of-way to total project requirements, consider the monetary and energy quantities required from the Miscellaneous Professional Services sector (see Table 2). This sector includes, but is not limited to, engineering. In 1963, the sector accounted for 7.2% of total highway construction dollar cost but only 1.8% of the total energy requirement. Thus, engineering alone accounted for <u>no more than</u> 1.8% of the total energy required for highway construction in 1963. It is assumed that the relative energy contributions of engineering and right-of-way to total project energy requirements do not change with time.

In 1963, the wholesale sector and the combination of the five transportation sectors each consumed about 4.0% of total highway costs. It is assumed that all wholesale costs and all transportation costs were devoted to construction materials, and that the relative energy contributions of these groups per dollar of construction costs remain unchanged over time. In 1970, about 45% of construction cost in the Federal-aid System went to materials. Under the stated assumption, about 10.2% of the cost of materials went to the wholesale sector and another 10.2% went to the combined transportation sectors. Thus 79.6% of the cost of materials was, on the average, consumed in the production of those materials. Wholesale markup will vary to some

extent between materials, and transportation costs are dependent on mode, type of material, and project location. For purposes of this model, however, it will be assumed that wholesale markup and transportation cost per dollar of each material is constant between materials.

In 1970, acquisition of thirteen materials comprised 90.2% of all materials costs for Federal-aid construction. These thirteen materials are those commonly used in highway construction and their statistical usage factors by type of highway and geographical location is well documented [30-33]. In 1963, the production alone of these thirteen materials or other materials which they composed (such as aggregate in ready-mixed concrete) amounted to 81.2% of the total energy (and 26.5% of the total dollars) used in highway construction. If it is assumed that the remaining 9.8% (dollarwise) of materials were on the average as energy intensive as the other 90.2%, then total materials production would account for 90.1% of the 1963 total energy requirement. Through application of the appropriate energy I/O factors, it can be shown that production, transportation, and wholesaling of material amounted to 94.79% of all energy consumed by highway construction in 1963. The remaining 5.21% of the energy required is estimated to be consumed by engineering and right-of-way, construction equipment, and contractor overhead. Average unit dollar costs for the so-called thirteen primary materials have been computed for the 1970 Federal-aid Primary System from References

30 through 33. These values and the respective unit energy costs for 1970 (including wholesaling and transportation) are itemized in Table 3. It should be stated that these unit energy values are intended for collective use in

Table 3 Unit Monetary and Estimated Energy Costs for 1970 Federal-aid Highway Construction Materials

Material	Unit	Unit Cost (dollars)	Unit Energy ($BTU x 10^{-5}$)
Cement	1000 barrels	4,619.39	12,238
Bitumens	Tons	27.73	196
Concrete pipe	Tons	37.08	24
Clay pipe	Tons	112.82	179
Lumber	1000 board feet	137.04	44
Timber piling	1000 linear feet	1,354.17	1,029
Petroleum products	1000 gallons	327.32	2,302
Explosives	1000 pounds	115.38	211
Structural steel	Tons	248.43	418
Reinforcing steel	Tons	192.99	187
Culvert steel	Tons	414.85	328
Miscellaneous steel	Tons	491.67	444
Aggregates purchased	1000 tons	3,008.06	1,995
Aggregates produced	1000 tons	126.10	84

estimating the energy cost for highway construction. Because of the somewhat crude assumptions of equal transportation and wholesaling costs per dollar of production cost for each of these items, it is felt that use of these unit energy requirements on an individual item basis is unjustified.

The values of primary materials given in Table 3 include both the effects of energy use/GNP change between 1963 and 1970 and the error involved in using final demand primary energy coefficients for direct contributors. Use of the previously stated assumptions permits the description of a simple mathematical model using the values from Table 3.

$$I_c = 1.1696 \sum_{i=1}^{14} v_i t_i \qquad (8)$$

where

I_c = total energy required for construction of a given highway or highway section

v_i = the total quantity of primary material i required

t_i = the total primary energy coefficient, including transportation and sales, for primary material i.

The multiplier, 1.1696, corrects for other materials, construction equipment, contractor's overhead, and engineering and right-of-way. The model may be verified on a macroscopic scale by placing Herendeen's total primary energy coefficient for new highway construction on a construction cost basis for 1970 and comparing this with model-generated results for estimated material usage for all U.S. highways for the 1969-1970-71 period [30-33]. The model-generated result

is 0.9618×10^5 BTU/$ of construction, and the corresponding modified Herendeen value is 0.9333×10^5 BTU/$ of construction. The difference of only 3% is fortuitous, considering the assumptions used in model development.

Topography, type of roadway, choice of surface material, etc., may cause considerable variation in energy requirements per dollar of construction cost. This may be observed from Table 4, in which model-generated total primary energy requirements, based on the usage factors from References 30-33, for each of the fifty states for the Federal-aid Primary System are listed for the years 1970-71-72. The breakdown of Table 4 into rural and urban locations for both Interstate and other Federal-aid Primary System construction permits rapid estimation of project energy requirements when construction costs are known. The preferred technique, of course, is to use the model and anticipated material requirements to estimate the energy expenditure for construction. It is noted that the data provided in Table 4 may not be used to imply a relationship between energy required per unit length of similar construction between two states because of the widely varying dollar cost per mile of construction between states.

The energy-based benefit/cost ratio requires that highway construction be included on an annual basis. This is accomplished by dividing the total construction energy requirement by the estimated lifetime. Winfrey [16] provides estimates of lifetimes for several types of pavements.

Table 4 Unit Energy Requirements for Federal-aid Primary System Highway Construction 1970-71-72

STATE	ENERGY PER DOLLAR OF CONSTRUCTION COST ($BTU \times 10^{-5}/\$$)			
	INTERSTATE SYSTEM		FEDERAL-AID PRIMARY SYSTEM (EXCLUSIVE OF INTERSTATE)	
	RURAL	URBAN	RURAL	URBAN
Alabama	1.3237	0.8389	1.2948	0.8689
Alaska	No work	No work	0.5558	0.9210
Arizona	1.1104	0.8429	0.8645	0.7300
Arkansas	1.0884	0.4257	1.1906	0.9817
California	0.8553	0.5930	0.6949	0.6329
Colorado	1.1561	0.6421	1.2030	0.6454
Connecticut	0.7679	0.5809	0.6388	0.6043
Delaware	0.6671	0.4638	1.1094	0.7952
Florida	1.3266	0.5247	0.9871	0.8323
Georgia	1.1268	1.0829	1.1575	0.8984
Hawaii	0.3822	0.3359	0.6089	0.5141
Idaho	1.3904	No work	0.9137	0.8462
Illinois	0.9440	0.6019	0.8631	0.7355
Indiana	0.8629	0.6660	0.9570	0.7617
Iowa	1.2078	0.8580	1.0749	0.8157
Kansas	1.2524	0.7808	1.3698	0.8426
Kentucky	0.8508	0.6470	0.8793	0.8702
Louisiana	0.6610	0.4602	0.9200	2.0726
Maine	0.9541	0.6613	0.8925	0.7062
Maryland	0.8662	0.5828	1.0143	0.5738
Massachusetts	0.6937	0.6031	0.7637	0.5863
Michigan	0.9820	0.4827	0.8050	0.4804
Minnesota	1.1423	0.6654	1.4867	0.8168
Mississippi	0.9128	1.0170	0.8062	0.7259
Missouri	0.8151	0.7013	0.8870	0.6782
Montana	1.0310	1.1918	1.3931	0.7488
Nebraska	1.2072	0.6087	1.7554	0.7213

Table 4 - continued.

STATE	ENERGY PER DOLLAR OF CONSTRUCTION COST ($BTU x 10^{-5}/\$$)			
	INTERSTATE SYSTEM		FEDERAL-AID PRIMARY SYSTEM (EXCLUSIVE OF INTERSTATE)	
	RURAL	URBAN	RURAL	URBAN
Nevada	1.2080	0.6973	1.1300	0.7972
New Hampshire	0.6942	0.7984	0.8522	0.5359
New Jersey	0.5990	0.4566	0.8870	0.5293
New Mexico	1.2150	0.9181	1.5910	1.1913
New York	0.5482	0.4123	0.5446	0.4657
North Carolina	1.1666	0.8952	0.9753	0.8652
North Dakota	1.3844	0.5832	2.8380	0.8785
Ohio	0.8342	0.6456	0.8163	0.6667
Oklahoma	2.0317	0.8792	1.6752	1.2401
Oregon	0.9764	0.7744	0.8079	0.6326
Pennsylvania	0.8385	0.5755	0.6220	0.7723
Rhode Island	0.6882	0.4862	0.3651	0.6074
South Carolina	1.4963	0.8500	1.1580	1.2641
South Dakota	1.0932	0.2826	1.8838	0.9703
Tennessee	1.2471	0.8495	1.1864	0.9592
Texas	1.3904	0.8137	1.0050	0.9884
Utah	1.1975	0.7434	1.2420	0.9670
Vermont	0.8562	No work	0.7236	0.7834
Virginia	0.9996	0.7307	0.9527	0.6789
Washington	0.8362	0.7187	0.8191	0.7196
West Virginia	0.7954	0.4149	0.5796	0.4587
Wisconsin	1.3415	0.7158	1.0445	0.8619
Wyoming	1.5418	0.5845	1.4493	0.5870
U.S. Averages	1.0051	0.6455	1.0126	0.7280
1969-1970-71 Averages	1.0518	0.6893	1.0651	0.7835

Energy Requirements for Acquisition of Buses

Bus priority treatments involving reserved lanes or exclusive right-of-way have become increasingly applied worldwide and are now over 200 in number [34]. Transportation projects of this nature, where bus transit is a design factor, should logically consider the cost of the vehicles used as a capital equipment investment.

The I/O sector "Motor vehicles and parts" applies to both automobiles and buses. In 1970, the average automobile produced weighed 3,966 pounds [35] and, as stated earlier in this chapter, 129×10^6 BTU were required to manufacture it. It is estimated, then, that the resulting manufacturing energy requirement of $.32526 \times 10^5$ BTU per pound applied to buses as well as automobiles. The energy required to manufacture a 53-passenger bus weighing 21,370 pounds and selling for $45,000 is 695.1×10^6 BTU. In 1970, 6.55 million cars were manufactured in the U.S. with a wholesale value of $14.5 billion [36]. Based on an average weight of 3,966 pounds, the wholesale price for automobiles is $1.7915 per pound. The wholesale cost of the 21,370-pound bus, based on this cost-to-weight ratio, is $38,284. It is assumed that the remaining $6,716 is involved in wholesaling the bus at the approximate 1970 value of $.0276 \times 10^5$ BTU/$. The total estimated energy required for acquisition of a 53-passenger bus, then, is 713.6×10^6 BTU.

Service lifetime for buses is estimated to be 15 years [37,38]. On this basis, acquisition of a 53-passenger

bus is estimated to require an average energy expenditure of 47.58×10^6 BTU/year.

CHAPTER IV

OPERATION AND MAINTENANCE REQUIREMENTS

In that this dissertation considers both bus transit and highway construction as potential transportation system investments, analysis of the energy requirements for operation and maintenance may be considered separately for the two investment classes. The energy-based I/O technique, described in Chapter III is the foundation for these analyses.

Highway Maintenance and Operation

Highway maintenance normally implies general maintenance to the roadway surface, structures, shoulders and side approaches, and roadside and drainage. Also included is unusual maintenance such as floods, earthquakes, etc. Annual operating expenses involve administration and traffic services, such as law enforcement, lighting, and snow and ice control. Winfrey [16] states that administrative costs are usually about the same for all mutually exclusive alternatives and can safely be omitted in engineering economy analyses. As administration is highly labor intensive, this would especially hold true for energy-based analyses.

Because of the relatively low degree of dissagregation of the 367-sector economy used in Reference 27, an analysis of the type performed for new highway construction (Chapter III) is not possible. However, as the same primary materials are involved (although in relatively different quantities), it is felt that use of the material-based model expressed by Equation 8 would not be an unreasonable approximation for operations and maintenance energy. Unfortunately, information at this level of detail is not usually available for the project alternatives under investigation, and operations and maintenance energy may require quantification on a monetary basis. The error involved in making a monetary-based estimate for operations and maintenance is not as severe as that which would be experienced in new construction because of the difference in labor intensity. For example, 55.6% of the typical operations and maintenance dollar is devoted to labor [19] while only 25.5% of the new construction dollar went to labor in 1970 [39]. As stated previously, there is no energy attributed to labor expenditures. For purposes of a monetary-based analysis, it will be considered that highway maintenance and highway operations fall under the I/O headings "Maintenance and repair construction, all other" and "Other state and local government enterprises," respectively. From these classifications, estimated 1970 total primary energy coefficients are assumed to be 0.55707×10^5 BTU/$ for maintenance and 0.74936×10^5 BTU/$ for operations.

The funds required for upkeep and operation of a highway are highly variable depending on such factors as weather, traffic volumes, soil conditions, and roadway physical characteristics including structures, pavement type and width, vertical grades, shoulder width, and embankment slopes. Operations and maintenance cost estimates are normally based on existing records for similar highway types and locations plus estimates based on judgment. Estimates of the energy expended per mile for several classes of state-administered highways in each of the fifty states during the year 1970 are shown in Table 5. The values listed are based on the dollars spent for physical maintenance and for those spent on operations, including law enforcement but excluding administration. For computational purposes, it was assumed that the ratio of physical maintenance to operations expenditures was the same for each highway class within a given state. The Table 5 values are based on records for a single year, and in some cases may not be typical. This may be suspected for the few cases of extreme variation in relative magnitudes of energy requirements for given highway classes. Such extreme variations from the mean, as in the case of rural primary state highways in Connecticut, cannot be attributed to the assumption of a fixed maintenance-to-operations ratio because of the similarity in magnitude of the two total primary energy coefficients used for operations and maintenance energy estimates.

Table 5 Operations and Maintenance Energy Expenditures for State-administered Highways - 1970 (administration excluded)

STATE	ENERGY EXPENDED FOR OPERATIONS AND MAINTENANCE (BTU/MI.x10^{-8})			
	PRIMARY STATE HIGHWAYS (RURAL)	SECONDARY ROADS UNDER STATE CONTROL	MUNICIPAL EXTENSIONS OF STATE SYSTEMS	OTHER STATE ROADS
Alabama	1.74867	0.54258	1.31769	-
Alaska	3.62888	-	1.93224	0.20016
Arizona	2.59249	-	4.63568	-
Arkansas	0.90196	-	1.63642	-
California	5.35761	-	18.79211	0.04770
Colorado	1.83475	-	4.38418	-
Connecticut	72.36887	0.09599	3.20457	0.60941
Delaware	1.15186	-	4.08174	-
Florida	2.22399	0.82852	1.12644	-
Georgia	1.19658	-	1.36254	-
Hawaii	5.47764	1.75716	3.53611	-
Idaho	1.51293	-	1.36063	-
Illinois	4.38826	-	3.09120	-
Indiana	2.77223	-	2.50067	27.06699
Iowa	2.41868	-	1.23910	0.46348
Kansas	2.11856	-	1.36945	7.90916
Kentucky	9.15594	-	1.40178	-
Louisiana	2.40708	1.38221	1.50962	1.99293
Maine	2.89059	0.84736	0.51069	7.72455
Maryland	8.29752	4.52299	-	-
Massachusetts	26.85915	-	3.03113	28.66007
Michigan	4.48524	-	2.94055	-
Minnesota	2.25040	-	1.29515	-
Mississippi	0.93797	-	0.92334	-
Missouri	1.23351	1.43059	1.94487	-
Montana	1.17148	0.05906	0.88408	-

Table 5 - Continued.

STATE	ENERGY EXPENDED FOR OPERATIONS AND MAINTENANCE ($BTU/MI.x10^{-8}$)			
	PRIMARY STATE HIGHWAYS (RURAL)	SECONDARY ROADS UNDER STATE CONTROL	MUNICIPAL EXTENSIONS OF STATE SYSTEMS	OTHER STATE ROADS
Nebraska	1.13213	-	1.09971	0.55690
Nevada	1.82553	0.57010	6.45175	-
New Hampshire	5.22494	2.94740	0.19319	26.46389
New Jersey	12.81607	-	33.22166	1.68573
New Mexico	1.26787	-	-	-
New York	4.56199	-	21.55666	25.26213
North Carolina	2.25445	0.61331	1.06960	-
North Dakota	0.69313	-	-	-
Ohio	3.31332	-	0.85003	0.09949
Oklahoma	1.69012	-	-	-
Oregon	3.00291	1.66293	1.67639	0.03000
Pennsylvania	1.48846	3.67062	2.10034	4.61399
Rhode Island	5.03839	-	5.70412	2.23807
South Carolina	1.41589	0.51631	0.38875	0.03002
South Dakota	0.74556	-	0.09344	-
Tennessee	2.26173	-	1.53258	-
Texas	0.98762	-	2.23904	-
Utah	1.86112	-	-	-
Vermont	3.73390	-	-	0.92871
Virginia	3.00416	0.71561	1.45428	-
Washington	4.95286	-	8.65830	0.00318
West Virginia	2.78140	0.46625	2.02064	1.68346
Wisconsin	2.39758	-	1.19984	0.19230
Wyoming	1.03715	-	0.42105	-
Averages	2.37272	1.07196	3.01902	3.39669

Bus System Maintenance and Operation

In the structure of the benefit/cost equation, the operations and maintenance cost terms are conceptually those associated with capital investments. Thus, operation and maintenance of bus systems should be considered as such only if the system is included as a design factor for a given alternative. Where bus operations exist independently of proposed alternatives, they logically belong to the class of road-user costs. As both operation and maintenance cost and road-user cost terms have the same sign and are both contained in the numerator of the benefit/cost ratio expression, it does not matter mathematically which of these terms contains the effective bus operations and maintenance costs, i.e., positioning of these costs is conceptual rather than mathematical.

Bus system maintenance and operation can be divided into two cost categories: one which contains those cost items directly associated with revenue equipment, and a second consisting of other items which pertain to overall system operation such as administration, maintenance of buildings and grounds, advertising, etc. It is felt that in situations where bus operations belong in the road-user class, the second category may be omitted, as, in the case of roadway maintenance, it could reasonably be assumed that these costs would be equal between alternatives. Furthermore, this approach is completely analogous to the treatment of other commercial vehicles in traditional analyses.

However, when bus operations are considered as part of the capital investment, those costs not directly associated with revenue equipment must logically be accounted for.

Those items which are directly attributable to revenue equipment (such as fuel, oil, and maintenance of revenue equipment) are analyzed in the same manner regardless of whether or not bus operations are project related; hence their analysis could be described either in this chapter or in Chapter V, which treats road-user costs. Because of the theoretical commonalities between automobiles, trucks, and buses, discussion of bus system revenue equipment will be deferred to Chapter V.

In a comparison of transit cost models, Miller and Rea [40] concluded that four-variable unit cost models, such as that developed by Ferreri [41], were superior to the others considered (four-variable regression and slowness function). The linear four-variable unit cost model, as used by Ferreri, is based on the relationships between cost account items and the following four systems-related independent variables: vehicle-hours, vehicle-miles, peak hour vehicles, and revenue passengers. The validity of the linear four-variable unit cost model was established through regression analyses based on cost data from numerous bus operations around the country [40,41]. Because of differences in unit costs between systems, models of this type are based, if possible, on data from the local operation. These differences are attributed to the wide variation in sizes of the

companies, age and condition of equipment, and labor conditions.

The operations and maintenance costs not considered directly associated with revenue equipment and the variables with which they are assumed to be linearly related are identified in Table 6. The total primary energy coefficients assumed for each of these items have been adjusted to represent 1970 values and are included in Table 6. A general mathematical model for estimating annual energy required for bus system operations and maintenance items not directly associated with revenue equipment is expressed below.

$$K_{N.R.} = (24611u_1 + 550707u_2 + 59151u_3 + 26616u_4)PV + (36469u_5)VM + (26089)RP \qquad (9)$$

where

$K_{N.R.}$ = annual energy expense for operations and maintenance items not directly associated with revenue equipment (BTU/year)

PV = number of peak hour vehicles required

RP = total annual revenue passengers

u_1 = unit cost for maintaining service equipment ($/peak hour vehicle)

u_2 = unit cost for maintaining buildings and grounds ($/peak hour vehicle)

u_3 = unit cost for station expenses ($/peak hour vehicle)

u_4 = unit cost of administration ($/peak hour vehicle)

u_5 = unit cost of traffic and advertising ($/vehicle mile)

u_6 = unit cost for insurance and safety (\$/revenue passenger)

VM = total annual vehicle miles traveled.

Use of the model described above requires that unit costs be either based on or modified to 1970 levels.

Table 6 Operations and Maintenance Allocations for Items not Directly Associated with Bus Revenue Equipment

ITEM	ENERGY COEFFICIENT (BTU/\$)	DEPENDENT VARIABLES		
		VEHICLE MILES	PEAK HOUR VEHICLES	REVENUE PASSENGERS
Maintain service equipment	24611		x	
Maintain buildings and grounds	55707		x	
Station expenses	59151		x	
Traffic and advertising	36469	x		
Insurance and safety	26089			x
Administration and general	26616		x	

The model has been calibrated for the Miami, Florida bus operation. The result, based on 1970 operating expenses and statistics from the Metropolitan Dade County Transit Authority, is the three-term reduced model given below.

$$K_{N.R.} = (1.57085\text{x}10^8)PV + (589.875)VM + (411.580)RP \quad (10)$$

Based on model output, the Miami operation consumed a total of $7.8\text{x}10^{10}$ BTU in 1970 for the class of items under consideration. Of the six items in the class, maintenance of

service equipment and maintenance of buildings and grounds combined accounted for less than 1% of this energy. Each of the remaining four items had a relative energy contribution of 11% or more.

CHAPTER V

ROAD-USER COSTS

Road-user energy costs are quantified in terms of fuel, oil, maintenance, tires, "depreciation," and accidents. For a single vehicle, these terms, with the exception of accidents, are related to the following primary variables: speed, speed changes, stops, surface, grade, curvature, and distance traveled. Analysis procedures then require that a facility be divided into sections characterized by essentially the same volumes, grade, curvature, and speeds. Demand, capacity, and geometrics are elements of the design procedure and are assumed to be known for each alternative. Estimates of average speeds for different sections may be obtained from the "Highway Capacity Manual" [42]. These procedures are consistent with those used in traditional economic analyses, and a detailed discussion of them here is considered unwarranted. Curry and Anderson [43] provide an excellent framework for analysis of road-user costs which separately considers peak periods (including queueing) and off-peak periods.

This chapter will analyze road-user cost items in terms of primary variables. The two primary data sources

used are Claffey [13] and Winfrey [16]. Use of these sources largely reflects the findings of the comparative analysis performed by Curry and Anderson [43]. Running cost data are assembled in terms of a "composite" automobile weighing about 4,000 pounds and two classes of trucks - single-unit gasoline-powered trucks of about 12,000 pounds and diesel combination tractor semi-trailer (3-S2) trucks of about 50,000 pounds. It is suggested in Reference 43 that data for the single-unit truck class also be used for buses. Road-user energy data are presented in Tables 7-16. These running cost data represent the combined energy consumed in fuel, oil, maintenance, depreciation, and tire wear. The development of the road-user energy tables and discussions of nontabularized items are given in the remainder of this chapter.

Fuel Consumption

Fuel and oil are the most energy-intensive items (on a dollar basis) of all those that determine road-user energy requirements. These total primary energy coefficients (BTU/$) are on the order of ten times as large as the others. It could logically be expected, then, that passenger car fuel consumption is the largest single energy factor involved in typical analyses of road-user energy.

Table 7 Energy Requirements at Uniform Speeds and Grades - Composite Automobile

Unit: BTU/vehicle-mile

Grade (%)	Speed (miles/hour) 10	20	30	40	50	60	70
-10	8,180	4,990	3,620	3,430	2,740	2,730	3,520
- 8	8,180	4,990	3,620	3,430	3,070	3,700	4,950
- 6	8,180	4,990	3,620	3,430	3,710	4,970	6,390
- 4	8,180	4,990	3,780	3,750	4,820	6,260	7,660
- 2	8,980	5,940	5,060	5,500	6,270	7,210	9,110
0	13,280	9,620	8,570	8,860	9,770	10,720	12,140
2	15,670	12,810	11,120	11,420	12,650	13,590	14,850
4	18,220	15,370	14,000	13,970	14,720	16,320	17,730
6	21,090	18,230	16,870	16,840	18,070	19,350	20,920
8	24,600	22,060	21,340	21,310	22,230	23,500	25,070
10	30,330	27,160	26,130	26,420	27,340	28,610	30,180

Table 8 Energy Requirements at Uniform Speeds and Grades - 12,000-Pound Single-Unit Truck

Unit: BTU/vehicle-mile

Grade (%)	Speed (miles/hour) 10	20	30	40	50	60
-10	13,840	9,310	7,930	7,200	7,260	7,480
- 8	13,840	9,310	7,930	7,360	7,260	8,280
- 6	13,840	9,310	8,100	8,010	9,020	11,150
- 4	13,840	9,310	8,420	9,130	11,250	14,190
- 2	14,490	10,750	10,670	12,160	15,570	18,660
0	17,560	13,990	14,850	17,140	20,200	23,770
2	24,970	22,550	23,540	26,580	29,450	-
4	33,850	31,430	33,190	37,640	-	-
6	41,910	39,020	41,390	-	-	-
8	52,240	52,090	53,130	-	-	-
10	63,200	68,090	-	-	-	-

Table 9 Energy Requirements at Uniform Speeds and Grades - 50,000-Pound 3-S2 Tractor Semi-trailer

Unit: BTU/vehicle-mile

Grade (%)	Speed (miles/hour) 10	20	30	40	50	60
- 8	36,860	-	-	-	-	-
- 6	33,220	15,000	-	-	-	-
- 4	28,120	11,430	7,830	-	-	-
- 2	31,950	13,900	9,360	10,120	14,150	-
0	45,620	28,410	24,400	24,910	29,100	36,430
2	67,010	55,830	54,520	57,710	-	-
4	87,250	83,540	88,920	-	-	-
6	105,850	110,980	-	-	-	-
8	122,790	138,150	-	-	-	-

Table 10 Excess Energy Requirements on Horizontal Curves (relative to level tangent) - Composite Automobile

Unit: BTU/vehicle-mile

Degree of Curve	Speed (miles/hour) 10	20	30	40	50	60	70
0	0	0	0	0	0	0	0
2	10	20	200	830	1,730	3,290	5,550
4	30	50	390	1,960	3,900	7,450	11,500
6	60	100	610	3,170	6,910	12,780	-
8	80	170	1,120	5,030	13,280	-	-
10	120	400	2,200	8,070	22,020	-	-
12	270	1,080	3,570	11,520	38,970	-	-

Table 11 Excess Energy Requirements on Horizontal Curves (relative to level tangent) - 12,000-Pound Single-Unit Truck

Unit: BTU/vehicle-mile

Degree of Curve	Speed (miles/hour) 10	20	30	40	50	60
0	0	0	0	0	0	0
2	270	320	440	520	1,430	2,970
4	430	660	890	1,690	4,640	-
6	500	1,180	1,700	4,040	9,650	-
8	660	1,660	2,980	6,920	15,010	-
10	810	2,250	4,420	10,690	-	-
12	960	2,750	6,460	15,910	-	-

Table 12 Excess Energy Requirements on Horizontal Curves (relative to level tangent) - 50,000-Pound 3-S2 Tractor Semi-trailer

Unit: BTU/vehicle mile

Degree of Curve	Speed (miles/hour) 10	20	30	40	50	60
0	0	0	0	0	0	0
2	990	970	1,160	1,450	3,960	8,130
4	2,030	2,020	2,330	3,790	9,310	-
6	2,830	3,020	3,510	7,160	16,470	-
8	3,680	3,900	4,730	11,650	25,880	-
10	4,330	4,690	6,510	17,280	37,660	-
12	4,810	5,520	9,720	24,360	-	-

Table 13 Excess Energy Requirements Due to Speed Changes - Composite Automobile

Unit: BTU/speed change cycle

Initial Speed	Speed Reduced to and Returned from (miles/hour)						
	Stop	10	20	30	40	50	60
10	340	-	-	-	-	-	-
20	1,320	610	-	-	-	-	-
30	2,080	1,310	690	-	-	-	-
40	2,830	2,030	1,410	720	-	-	-
50	3,720	3,030	2,240	1,500	780	-	-
60	4,560	4,010	3,200	2,410	1,580	820	-
70	5,300	5,040	4,140	3,320	2,500	1,680	900

Table 14 Excess Energy Requirements Due to Speed Changes - 12,000-Pound Single-Unit Truck

Unit: BTU/speed change cycle

Initial Speed	Speed Reduced to and Returned from (miles/hour)					
	Stop	10	20	30	40	50
10	920	-	-	-	-	-
20	2,710	1,340	-	-	-	-
30	4,780	3,380	1,870	-	-	-
40	7,210	5,780	4,250	2,430	-	-
50	10,120	8,650	7,080	5,250	3,020	-
60	13,680	12,170	10,560	8,690	6,450	3,660

Table 15 Excess Energy Requirements Due to Speed Changes - 50,000-Pound 3-S2 Tractor Semi-trailer

Unit: BTU/speed change cycle

Initial Speed	Speed Reduced to and Returned from (miles/hour)					
	Stop	10	20	30	40	50
10	2,570	-	-	-	-	-
20	8,400	5,260	-	-	-	-
30	15,780	12,500	7,750	-	-	-
40	25,330	21,890	17,440	11,020	-	-
50	37,990	34,170	29,560	23,490	14,780	-
60	54,790	50,410	45,170	38,820	30,450	19,430

Table 16 Energy Consumed in Idling

Vehicle	Energy Consumption (BTU/minute)
Composite Automobile	1,540
12,000 lb. Single Unit Truck	1,710
50,000 lb. 3-S2 Tractor Semi-trailer	1,190

The Automobile

The fuel consumption data collected by Claffey [13] are perhaps the most extensive set ever compiled in a form suitable for use in economic analysis of highways. These data were collected for five types of automobiles and presented primarily in the form of fuel consumption for

different combinations of speed and grade. Corrections for curvature, stops, speed changes, surface type, and altitude are provided. In addition, Claffey provides data for a "composite" automobile, based on a mix of consumption data for the five individual automobiles. This mix was based on a survey of over 35,000 vehicles in eight states.

Questions arise over whether or not Claffey's composite automobile data (or, for that matter, data for individual automobiles) are representative for the future. The production years of the models tested ranged from 1964 to 1968 and therefore a composite of data could not accurately be said to represent any particular model year. Since some of the models are over 10 years old, extension of data for a specific automobile to even the present time might be a source of concern. For example, considering the changes in horsepower, weight, pollution control devices, and optional power-consuming equipment that have occurred over time, one could logically ask whether or not fuel consumption varies between a 1964 and a 1975 Chevrolet and in what manner. While extensive testing of late-model automobiles has been conducted by the Environmental Protection Agency, this testing is performed under laboratory conditions and is based on a driving cycle [44,45]. These fuel consumption data cannot be related to project level variables and are of little use in determining differences in road-user fuel consumption. Finally, the effects of

changes in composition of the automobile population over time are unknown. It can certainly be anticipated that the future automobile population will contain a higher proportion of small cars as the fuel situation worsens.

In an attempt to establish the feasibility of modifying Claffey's data to account for changes in vehicle characteristics that have occurred in the last 10 years, several analyses were conducted. While these analyses did not, for the most part, produce the desired results, they are described for record in the paragraphs that follow.

Theory and analysis

Newton's second law states that the net force acting on a body is equal to its time rate of change of momentum. The general mathematical expression is

$$\Sigma F = \frac{d(mV)}{dt}$$

where

ΣF = the sum of forces acting on the body

m = the mass of the body

t = time

V = the velocity of the body.

Expansion of this derivative gives

$$\Sigma F = m \frac{dV}{dt} + V \frac{dm}{dt} \tag{11}$$

For an automobile, the rate of change of mass with respect to time is almost totally due to fuel consumption. Because of the low flow rates encountered, it may be assumed that

$\frac{dm}{dt}$ is equal to zero. Equation 11 may now be expressed as

$$\Sigma F = ma \tag{12}$$

where a = the instantaneous acceleration of the body ($\frac{dV}{dt}$).

For performance considerations, the important forces acting on an automobile are the driving forces from the powerplant, aerodynamic resistance, tire rolling and cornering forces, and the weight of the vehicle. These forces or their components acting in the direction of motion and the symbols used to represent them are shown in Figure 3. Substitution of these terms into Equation 12 and replacement of the mass term by its weight-based equivalent give

$$F_t - (F_r + F_a + F_c + W \sin \theta) = \frac{W_e}{g} a \tag{13}$$

where

g = gravitational constant

W = total vehicle weight

W_e = total vehicle weight plus the translational equivalent of the rotating masses

θ = grade angle.

Thus, acceleration is proportional to the difference between tractive effort (F_t), the engine-derived force which propels the vehicle by delivering torque to the rear axle, and the sum of the external forces acting on the vehicle.

The $W \sin \theta$ term in Equation 13 is the vector component of the weight force acting in the plane of the roadway.

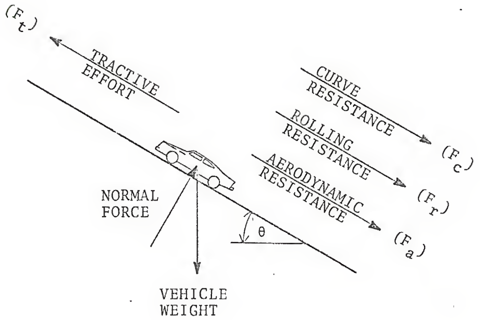

Figure 3 Forces Acting on an Automobile

This force, as indicated by its sign, acts in a rearward direction for positive grades and in a forward direction for negative grades.

Aerodynamic resistance, or drag (F_a), always acts opposite to the direction of motion. Drag is a function of dynamic pressure (q), vehicle frontal area (A), and a shape-related "drag coefficient" (C_d). The empirically determined drag coefficient varies considerably with vehicle shape but, for the typical range of automobile speeds, is usually considered constant for a given vehicle. The appropriate expression for drag is

$$F_a = C_d q A \tag{14}$$

Using an alternative form for dynamic pressure, Equation 14 becomes

$$F_a = C_d(1/2\ \rho V_r^2)A \tag{15}$$

where

ρ = density of the ambient air

V_r = velocity of the wind relative to the vehicle.

Relative wind velocity is the vector sum of vehicle and wind velocity. While the effects of wind may have a large influence on drag, these effects are unpredictable. For the purposes of this dissertation, it will be assumed that the net effects of wind are zero, i.e., it is assumed that F_a is proportional to vehicle velocity squared for a given drag coefficient and density condition.

While theory exists for the resistance of rigid wheels on rigid surfaces, Bekker [46] states that there is no such theory which adequately represents the resistance of an elastic tire on a hard surface. Rolling resistance of tires on pavement, therefore, is a quantity which must be treated empirically. This resistance arises mainly from the constant flexing of the tires and is sensitive to tire design, materials, load, degree of inflation, and speed [47]. The variation of rolling resistance with velocity is qualitatively depicted in Figure 4. For the typical range of automobile speeds, this variation is nearly linear. An expression for rolling resistance that includes the effects of grade is that given by Smith [48]

$$F_r = W(RR + RRC\ V)S \tag{16}$$

where RR and RRC are coefficients of tire rolling resistance

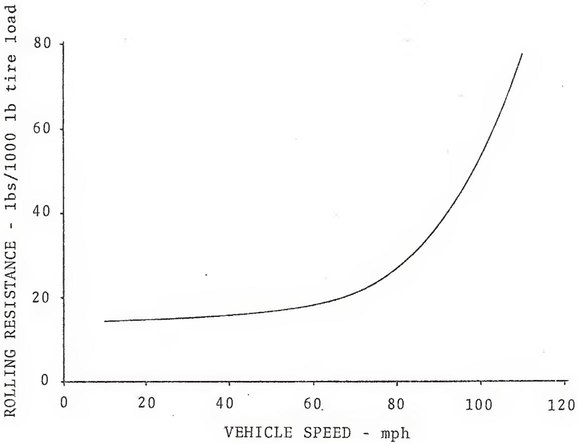

Figure 4 Typical Variation of Rolling Resistance with Speed

and S is a road surface factor. The value of S is 1.0 for highways, and is greater for rougher terrain. The coefficients of rolling resistance are of the form

$$RR = \frac{a_1}{W(S + \tan\theta)}$$

$$RRC = \frac{b_1}{WS}$$

where a_1 and b_1 are vehicle-dependent constants. For high-type pavements, Equation 16 may be written as

$$F_r = \frac{a_1}{1 + \tan \theta} + b_1 V \tag{17}$$

For an automobile to travel a curved path on a horizontal unbanked roadway, the front wheels must be turned to an angle (α) from the direction of travel. This produces a cornering force (F_α) normal to the plane of the wheel (see Figure 5). Components of this cornering force are 1) the centripetal force (F_1) which acts perpendicular to the direction of travel and produces the curved motion, and 2) a resisting force which acts opposite the direction of motion (F_c). The resisting force is a function of tire cornering stiffness and the square of the radius of curve to the center of gravity. It is directly proportional to the fourth power of velocity and the second power of weight. Corrections must be made for crowned roads and banked highways.

Tractive effort, F_t, is derived from the power delivered to the drive wheels from the engine. The spark-ignition Otto cycle internal combustion engine is that used in nearly all automotive applications. Performance data for this type of engine are normally expressed in terms of gross horsepower (or brake horsepower), engine speed, and brake specific fuel consumption (bsfc) under wide open throttle conditions. These characteristics are shown in Figure 6 for one automobile engine. Gross horsepower may be defined as that which is developed by the engine operating without normal running equipment and accessories, including fan,

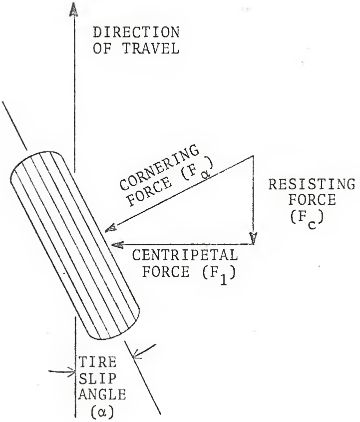

Figure 5 Wheel Forces for Turning Movement

pump, alternator or generator, air cleaner, and conventional exhaust system. For given operating conditions, fuel consumption may be expressed as

$$\dot{w} = bsfc \times P_b \qquad (18)$$

where

$\dot{w}$ = fuel weight flow rate (pounds/hour)

bsfc = brake specific fuel consumption (pounds/horsepower hour)

P_b = brake horsepower.

Assuming constant fuel density, Equation 18 may be rewritten

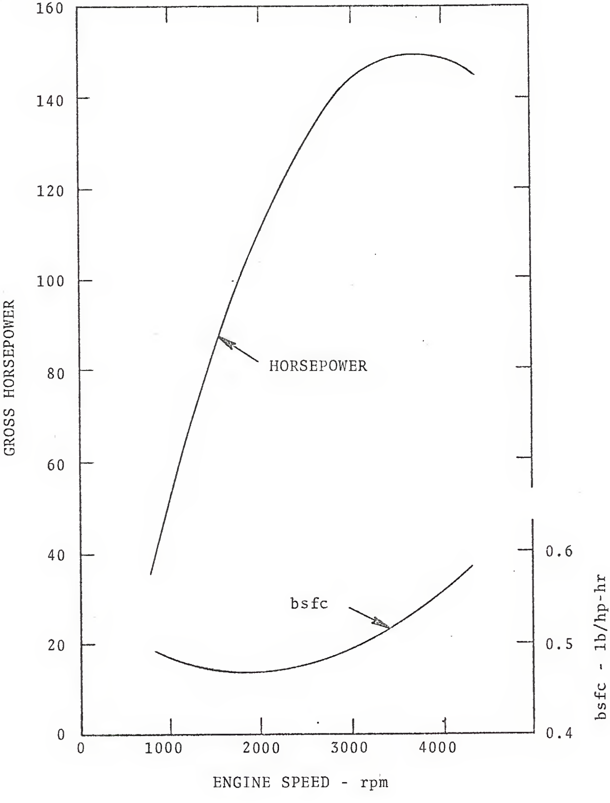

Figure 6 Spark Ignition Engine Performance Characteristics

in terms of volume flow rate

$$g = \xi \times bsfc \times P_b \tag{19}$$

where

g = fuel volume flow rate (gallons/hour)

ξ = fuel conversion factor from pounds to gallons (gallons/pound).

The most useful form of fuel consumption for purposes of road-user analysis is based on distance rather than time. This may be obtained by dividing volume flow rate by speed. Fuel consumption in gallons per mile (gpm), written as a proportionality, is

$$gmp \sim \frac{bsfc \times P_b}{V} \tag{20}$$

The gross horsepower developed by the engine is used to power both the drive wheels, engine equipment (fan, exhaust system, air cleaner, etc.), and convenience accessories such as power steering, power brakes, and air conditioning. The difference between gross horsepower and horsepower required for accessories is defined as net horsepower (P_N). Net horsepower is that which is available at the flywheel for use in vehicle propulsion at a fixed engine speed with the throttle wide open. Engine speed, total gear reduction, and effective wheel rolling radius can be used to determine vehicle operating speed. Conversely, for a given vehicle speed and gear ratio, engine speed may be obtained. The engine horsepower output required to sustain a given speed or to provide acceleration is regulated by throttle setting.

Engine horsepower (P_E) is defined here in terms of net horsepower, i.e., for wide open throttle, engine horsepower is equal to net horsepower. Because of losses incurred in transmission of power from the engine flywheel through the axle shafts, wheel horsepower (P_W) is less than engine horsepower. These power terms are related by the transmission efficiency factor, e

$$P_W = eP_E \tag{21}$$

The first step in analysis of the Reference 13 data was to investigate the effects of changes in automobile population on composite automobile fuel consumption. The automobile population from which the Reference 13 composite data were established consisted of 5% small cars, 10% compact cars, 65% standard-size cars, and 20% large cars. Volkswagen and Chrysler fuel consumption data were the bases for the small and large car categories, respectively. For comparison purposes, a new mix of automobiles was hypothesized in which 1) the percentage of small cars was doubled, and 2) this increase in small car population was derived solely from a corresponding decrease in large car population. Stated another way, the supposition was that one out of every four drivers of large cars began driving small ones, thereby doubling the percentage of small cars in the overall automobile population. Comparisons of fuel consumption data were made between the resulting hypothetical new composite automobile and the Reference 13

composite for speeds ranging from 10 to 70 miles per hour and grades ranging from -10% to +10%. It was found that the maximum difference in fuel consumption between the two populations was slightly over 5% of the Reference 13 composite. Under conditions of equal mileage driven at each speed and grade combination, the average error was about 2%. Even if <u>all</u> large car drivers began driving small cars (increasing the small car population by a factor of four), the resulting average error is still less than 9%. It was concluded that the composite automobile fuel consumption data given in Reference 13 are relatively insensitive to modest changes in automobile population.

The Reference 12 fuel consumption data for individual automobiles are given in plotted form as a function of constant speed for specified grades. Similar data for the composite automobile are provided in tabular form. The effects of speed changes, curvature, and surface on fuel consumption are treated in the form of corrections to these basic data sets. Several attempts were made to establish the framework of a general mathematical model, based on theory, which, for specific applications, would adequately duplicate the Reference 13 fuel consumption data. Such a model could be extremely useful for estimating differences in fuel consumption that might occur in future years due to changes in vehicle weight, frontal area, tires, etc., as well as changes in composition of the automobile population. While

a sufficiently accurate model was not obtained, it is felt that the general approach to model development, the comparative effects of various engine and power train submodels, and one particular area of model/data disagreement are worthy of discussion.

For constant speed on a straight roadway, the dynamical relationship of Equation 13 becomes

$$F_t - (F_r + F_a + W \sin \theta) = 0 \qquad (22)$$

That is, tractive effort must be equal to the sum of the external forces acting on the automobile. Tractive effort may be defined in terms of horsepower supplied to the wheels by

$$F_t = P_w \frac{375}{V}$$

where the units of F_t and V are pounds and miles per hour, respectively. Equation 22 may be rewritten in terms of wheel horsepower as follows:

$$P_w = \frac{V}{375} (F_r + F_a + W \sin \theta) \qquad (23)$$

where all external forces are expressed in pounds. Equation 23 may be written in terms of primary variables using the relationships given in Equations 15 and 17.

$$P_w = \frac{V}{375} \left[\frac{a_1}{1+\tan \theta} + b_1 V + C_d (1/2\ \rho V^2) A + W \sin \theta\right] \qquad (24)$$

$$P_w = \left(\frac{a_1}{375}\right) \frac{V}{1+\tan \theta} + \left(\frac{b_1}{375}\right) V^2 + \left(\frac{C_d \rho A}{750}\right) V^3 + (W) V \sin \theta \quad (25)$$

The terms in parentheses are constants for a given vehicle. Using the subscripted symbol C to represent these constants, Equation 25 may be reduced to the following simplified form:

$$P_w = C_1 \frac{V}{1+\tan\theta} + C_2V^2 + C_3V^3 + C_4V\sin\theta \qquad (26)$$

This is the general expression for wheel horsepower and is that used in all model structure.

Model 1. The first fuel consumption model tested is based on an assumption stated in Reference 48 that the net horsepower curve can be represented by a second degree polynomial in engine speed. Expressed mathematically,

$$P_N = A_0 + A_1N + A_2N^2 \qquad (27)$$

where

N = engine speed in revolutions per minute

A_0, A_1, A_2 = constants.

Fuel consumption, however, is a function of brake horsepower output, which includes accessory horsepower requirements. While accessory requirements were not known, the typical accessory data from Reference 49 indicated that it might be reasonable to assume that these, too, could be approximated by a polynomial in engine speed not in excess of degree two. Thus, it is implied that the gross horsepower curve is a second degree polynomial in engine speed. In an attempt to eliminate the effects of accessories in modeling fuel consumption, a fictitious volume-based fuel consumption curve based on net horsepower was assumed to exist. Because of the similarities in the assumed net

horsepower and brake horsepower curves, a "net" specific fuel consumption curve resembling the brake specific fuel consumption curve of Figure 6 was considered. The third degree polynomial in engine speed chosen to represent net specific fuel consumption (nsfc) is of the general form

$$\text{nsfc} = B_0 + B_1N + B_2B^2 + B_3N^3 \tag{28}$$

where the B's are constants. It was assumed for this model that net specific fuel consumption was independent of throttle setting. Thus, fuel flow rate in gallons per hour is expressed as the product of engine horsepower available for propulsion and net specific fuel consumption for a given speed.

$$\dot{g} = \text{nsfc} \times P_E \tag{29}$$

Conversion of Equation 29 to the more convenient form of gallons per mile gives

$$\text{gpm} = \frac{\text{nsfc} \times P_E}{V} \tag{30}$$

A constant transmission efficiency was assumed for Model 1. Engine horsepower is therefore directly proportional to wheel horsepower, and the functional forms of the two are identical, i.e., without loss of generality, engine horsepower may be expressed as

$$P_E = C_1 \frac{V}{1+\tan\theta} + C_2V^2 + C_3V^3 + C_4V\sin\theta \tag{31}$$

Finally, a fixed gear ratio was assumed. This implies a proportional relationship between vehicle speed

and engine speed. Expressed mathematically,

$$N = D_1 V$$

where D_1 is fixed for a given operating gear. The effect of this assumption is that net specific fuel consumption may be expressed in the same general form with vehicle speed substituted for engine speed. This relationship is

$$\text{nsfc} = B_0 + B_1 V + B_2 V^2 + B_3 V^3 \tag{32}$$

Substituting Equations 31 and 32 into Equation 30, fuel consumption is approximated by

$$\text{gpm} = (B_0 + B_1 V + B_2 V^2 + B_3 V^3)(C_1 \frac{1}{1+\tan\theta} + C_2 V + C_3 V^2 + C_4 \sin\theta)$$

Expansion of this equation gives the following general form for fuel consumption:

$$\text{gpm} = \beta_1 V + \beta_2 V^2 + \beta_3 V^3 + \beta_4 V^4 + \beta_5 V^5 + \beta_6 \frac{1}{1+\tan\theta} + \beta_7 \frac{V}{1+\tan\theta} + \beta_8 \frac{V^2}{1+\tan\theta} + \beta_9 \frac{V^3}{1+\tan\theta} + \beta_{10} \sin\theta + \beta_{11} V \sin\theta + \beta_{12} V^2 \sin\theta + \beta_{13} V^3 \sin\theta \tag{33}$$

This model is of zero-intercept form, and the thirteen terms it contains illustrates the degree of complexity involved in modeling fuel consumption under the most simple assumptions.

The model was evaluated using the BMD-02R stepwise regression digital computer program, documented in Reference 50. This program was chosen because of its capability to automatically ignore terms which do not

significantly improve the quality of the regression. Sometimes it is possible, then, to obtain a simpler model, i.e., one containing fewer terms than the original model. The data set used for Model 1 was restricted to speeds of 30 to 70 miles per hour in increments of 10 miles per hour and grades of -6% to +4% in 2% increments. While this restriction reduced the size of the potential data set to 30 points, it was deemed necessary in order to more accurately represent fixed gear operation.

While the model produced reasonable results at all positive grade and speed combinations, sizeable errors were involved in the 30 to 50 mile per hour speed range at grades of -6% and -2%. It was concluded, therefore, that Model 1 was inadequate.

Model 2. With the exception of the assumption of constant power transmission efficiency, the second model was the same as Model 1. For Model 2, the total driveline efficiency model of Smith [48] was chosen. This model is in part based on the tendency of the increase in viscous losses of the axle with road speed to compensate for the differences in losses of the various transmission gears. Smith states that test results indicate a relatively constant total driveline efficiency from the lowest to the highest gears at full throttle, and consistently lower efficiencies at part throttle. The mathematical expression for Smith's efficiency model is

$$e + e_f[1 - k(\frac{1}{L} - 1)] \tag{34}$$

where

e_f = driveline efficiency at full throttle

k = viscous loss factor (constant for a given vehicle)

L = percent throttle setting, defined as the ratio of P_E to P_W.

The variation of efficiency with throttle setting similar to that expected for an automobile is shown in Figure 7. By expressing efficiency and throttle setting in terms of horsepower, Equation 34 may be rearranged to give the following relationship:

$$P_E = \frac{P_W}{e_f(1+k)} + \frac{k}{1+k} P_N \tag{35}$$

From Equation 30, fuel consumption may be written

$$gpm = \frac{nsfc}{V} [\frac{P_W}{e_f(1+k)} + \frac{k}{1+k} P_N] \tag{36}$$

For fixed gear operation, net horsepower may be represented by a second degree polynomial in V. This polynomial and the relationships given in Equations 26 and 32 define the following general form for Equation 36:

$$\begin{aligned} gpm = {} & \beta_0 + \beta_1 V + \beta_2 V^2 + \beta_3 V^3 + \beta_4 V^4 + \beta_5 V^5 + \beta_6 \frac{1}{\tan\theta} \\ & + \beta_7 \frac{V}{1+\tan\theta} + \beta_8 \frac{V^2}{1+\tan\theta} + \beta_9 \frac{V^3}{1+\tan\theta} + \beta_{10} \sin\theta \\ & + \beta_{11} V \sin\theta + \beta_{12} V^2 \sin\theta + \beta_{13} V^3 \sin\theta + \beta_{14} \frac{1}{V} \end{aligned} \tag{37}$$

This model is of the same form as Model 1 with the addition of the intercept (β_0) and the β_{14} term. It should be mentioned that approximation of the net horsepower

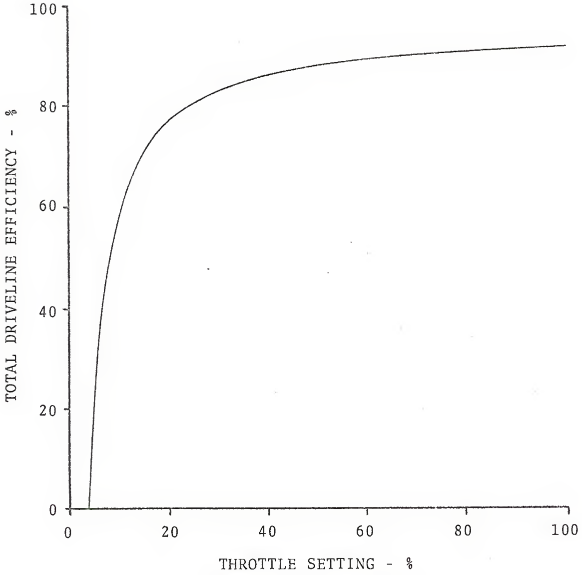

Figure 7 Typical Variation of Driveline Efficiency with Throttle Setting

curve with a third degree polynomial would leave this general form unchanged.

Stepwise regression based on the same data set used in Model 1 was employed in Model 2 evaluation. Results of this regression indicated a general improvement over

Model 1, although the errors encountered at speeds of 30 and 40 miles per hour and grades of -6% and -2% were still sufficiently large to prohibit recommendation of the model for general use. While Model 2 showed improvement over Model 1 at negative grades, some loss of accuracy was observed at zero grade.

Model 3. The relationship between engine speed and vehicle speed depends on effective wheel rolling radius, rear-axle ratio, and transmission gear ratio. For a given vehicle, transmission gear ratio is a function of speed, grade, and driver characteristics. In an attempt to qualitatively assess the influence of gear ratio on fuel consumption, a gear shift model based on speed alone was assumed. As the variation of engine speed with vehicle speed will resemble a step function at the point a gear change occurs, a hyperbolic tangent function was chosen to represent the change. The functional form of the relationship used is

$$R = D_0 + D_1 \tanh (D_2 + D_3V) \qquad (38)$$

where

D_0, D_1, D_2, D_3 = constants

R = engine speed divided by rear-axle speed.

Unfortunately, this structure is such that the coefficients cannot be determined in the regression process. From estimates based on the vehicle characteristics given by Claffey [13], the following model was selected:

$$R = 4.1165 + 1.0996 \tanh (8.6666 - 0.3689V) \tag{39}$$

The variation of R with speed is shown in Figure 8.

For a given gear ratio, engine speed is still proportional to vehicle speed. The relationship for engine speed is

$$N = D_4 VR$$

where D_4 is a constant related to effective wheel rolling radius. New expressions for net specific fuel consumption and net horsepower may now be written. Using Equation 28,

$$\text{nsfc} = B_0 + B_1 D_4 VR + B_2 D_4^{\,2} V^2 R^2 + B_3 D_4^{\,3} V^3 R^3$$

Without loss of generality, net specific fuel consumption can be expressed as

$$\text{nsfc} = B_0 + B_1 VR + B_2 V^2 R^2 + B_3 V^3 R^3 \tag{40}$$

Similarly, net horsepower may be written

$$P_N = A_0 + A_1 VR + A_2 V^2 R^2 \tag{41}$$

The variable drive train efficiency approximation used in Model 2 was also used in Model 3. Substitution of Equations 40 and 41 into Equation 36 establishes the following general form for fuel consumption:

$$\begin{aligned} \text{gpm} = {} & \beta_1 \frac{1}{\tan \theta} + \beta_2 V + \beta_3 V^2 + \beta_4 \sin \theta + \beta_5 \frac{1}{V} + \beta_6 R \\ & + \beta_7 VR^2 + \beta_8 \frac{VR}{1+\tan \theta} + \beta_9 V^2 R + \beta_{10} V^3 R + \beta_{11} VR \sin \theta \\ & + \beta_{12} V^2 R^3 + \beta_{13} \frac{V^2 R^2}{1+\tan \theta} + \beta_{14} V^3 R^2 + \beta_{15} V^4 R^2 \end{aligned}$$

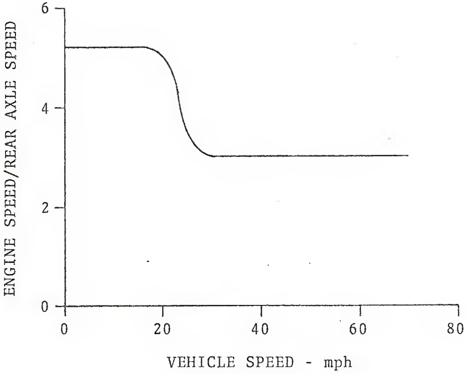

Figure 8 Assumed Variation of Engine Speed/Rear Axle Speed Ratio

$$+ \beta_{16}V^2R^2 \sin\theta + \beta_{17}V^3R^4 + \beta_{18}\frac{V^3R^3}{1+\tan\theta} + \beta_{19}V^4R^3$$

$$+ \beta_{20}V^5R^3 + \beta_{21}V^3R^3 \sin\theta + \beta_{22}V^4R^5 \qquad (42)$$

Assessment of Model 3 was based on a zero-intercept stepwise regression with 77 data points. These points were obtained from fuel consumption data for speeds of 10 to 70 miles per hour and grades from -10% to +10%. Data increments used were 10 miles per hour for speed and 2% for grade.

The errors resulting from this model were much larger than those observed from Models 1 and 2. The regression

was performed a second time with intercept (β_0) added. The effect of adding the intercept was to improve the fit. For the 30 to 70 mile per hour range, the model results were very similar to those of Model 2, and this model too was deemed inadequate for use. It was noted that the most significant errors were involved at a grade of -2% for speeds of 40 miles per hour and below.

Model 4. The final attempt to simulate fuel consumption involved a net specific fuel consumption model different from that of Models 1-3. The model used is based on the characteristics of the normalized brake specific fuel consumption map, shown in Figure 9 for one spark ignition internal combustion engine.

For a given engine speed (represented as percent of maximum in Figure 9), normalized brake specific fuel consumption appears to vary as a second degree polynomial in percent of maximum gross horsepower output for engine speeds less than 80% of maximum. In this range, brake specific fuel consumption for a fixed engine speed may be written in the general form

$$bsfc = E_0 + E_1 P_b + E_2 P_b^2 \tag{43}$$

As in earlier models, it was assumed that the relationship between net specific fuel consumption and engine horsepower would exhibit characteristics similar to those shown in Figure 9. However, while the relationship between brake specific fuel consumption and gross horsepower appears

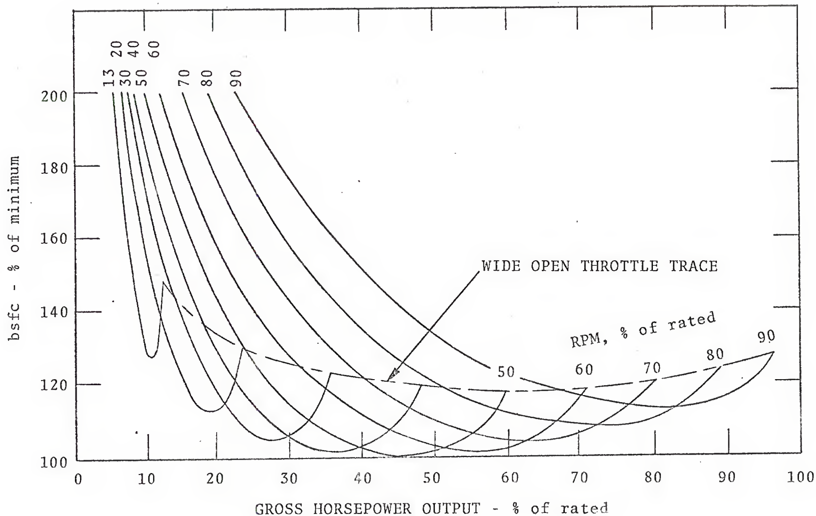

Figure 9 Normalized Brake Specific Fuel Consumption Map

to be parabolic for a given speed, the plots in Figure 9 show that these parabolas vary as some function of engine speed. The following general relationship was assumed for net specific fuel consumption:

$$nsfc = f_0(N) + f_1(N)P_E + f_2(N)P_E^2 \qquad (44)$$

where $f_0(N)$, $f_1(N)$, $f_2(N)$ are unknown functions of engine speed which define the variation in the parabolas. Model 4 contained the engine speed/vehicle speed (gear change) simulation used in Model 3. As only 77 data points were used in the analysis, it was necessary to assume constant driveline efficiency (as in Model 1) and to restrict the engine speed functions of Equation 44 to the first degree. The resulting expression selected for net specific fuel consumption is

$$nsfc = (\alpha_1 + \alpha_2 N) + (\alpha_3 + \alpha_4 N)P_E + (\alpha_5 + \alpha_6 N)P_E^2 \qquad (45)$$

where the α's are constants. Conversion to gallons per mile is obtained through Equation 30.

$$gpm = \frac{1}{V}[(\alpha_1 + \alpha_2 N)P_E + (\alpha_3 + \alpha_4 N)P_E^2 + (\alpha_5 + \alpha_6 N)P_E^3] \qquad (46)$$

Equation 46 was expanded to regression form using the assumed relationships for engine speed and engine horsepower. The result of this expansion is a 67-term zero-intercept model which, for brevity, will not be written here. Stepwise regression was performed on the model with intercept included so that 1) the best possible fit could be obtained, and 2) the magnitude of the intercept

could be observed. The 77-point data set used was the same as for Model 3, i.e., speeds from 10 to 70 miles per hour and grades from -10% to +10%.

The results of Model 4 were considerably better than any of the others tested. However, as large errors were encountered at speeds less than 50 miles per hour at -2% grade, this model, too, was considered inadequate. The intercept determined in the regression process was considerably different from zero and, in magnitude, was on the same order as intercepts obtained in other regressions.

Analysis conclusions. Of all the models tested, none were considered adequate for simulating fuel consumption. The fact that large errors were involved in the outputs of all models in the 10 to 40 mile per hour range at -2% grade was of particular interest. The automobile fuel consumption data for this range gathered by Claffey [13] show much lower consumption values than would be predicted by any of the models. In fact, application of Claffey's data to gently rolling terrain at relatively low speeds indicates that fuel consumption is lower (in some cases as much as 20% lower) than that on level terrain. While this phenomenon is contrary to what one would expect, Claffey recognized it early in his study and made numerous additional observations which verified it. None of the models analyzed exhibited this characteristic; model-generated data indicated that slightly *more* fuel would be consumed on rolling terrain. This is implied from the relationships used to

represent the external forces acting on the vehicle. Aerodynamic resistance always opposes motion and is independent of grade. Terrain, then, has no influence on this force. The component of vehicle weight acting in the plane of the roadway ($W \sin \theta$) opposes motion for positive grades but assists motion for negative grades. For equivalent uphill and downhill slopes, the net effect of this force is zero. Rolling resistance has two components, one of which opposes motion and is independent of grade. The other, given by

$$RR = \frac{a_1}{W(1 + \tan \theta)}$$

is a function of grade only and does contribute more resistance to uphill motion than to downhill. For example, let $a_1 = W = 1$ for simplicity, and compare grades of +10% and -10%. For a grade of +10%

$$RR = \frac{1}{1 + 0.1} = 0.9091$$

For a grade of -10%

$$RR = \frac{1}{1 - 0.1} = 1.1111$$

For zero grade, it may be seen by inspection that

$$RR = 1.0$$

For equal distances traveled at +10% grade and -10% grade, it may be shown that about 1% more energy (considering this force to be an isolated one) is required than if the equivalent distance were covered on a level roadway.

If the relationships used to represent the external forces acting on the vehicle are reasonable ones, then the rolling-grade phenomenon must be due to either the engine or driveline efficiency models.

A brief investigation of net specific fuel consumption characteristics was conducted. This study was based on the external force formulation used in Models 1-4 and the driveline efficiency model used in Models 2 and 3. While two vehicles were analyzed, the qualitative consumption characteristics were similar. For brevity, only one of these analyses, that of a 1965 Ford Falcon, will be discussed. This vehicle, tested by Claffey [13], had a gross test weight of 3,000 pounds and a frontal area of 26 square feet. The constants used in determination of rolling resistance were assumed to be approximately the same as for a pickup truck. The values used were those given by Smith [48].

$$a_1 = 0.0116$$

$$b_1 = 0.000228$$

Reference 16 gives a range of 0.4 to 0.5 for passenger car drag coefficient. Standard sea level conditions (ρ = 0.002378 slugs per cubic foot) and a drag coefficient of 0.5 were used in estimation of aerodynamic forces. Under the stated assumptions for the vehicle described, Equation 25 is used to define wheel horsepower requirements as a function of speed and grade.

$$P_w = 0.0928 \frac{V}{1+\tan\theta} + 0.001824V^2 + 0.0000886V^3$$

$$+ 8.0V \sin\theta \qquad (47)$$

The relationship between engine speed and vehicle speed was based on operation in the highest gear. From the data given in Reference 13 for this vehicle, the following relationship was obtained:

$$N = 42.09\ V \qquad (48)$$

Claffey [13] defines only two items concerning test vehicle engine characteristics: maximum net horsepower and engine speed. It was felt that an approximation of the relationship between net horsepower and engine speed based on the curve depicted in Figure 6 would be adequate for this qualitative analysis. First, regression was used to obtain a second degree polynomial which adequately represented Figure 6. Then, the polynomial was adjusted so that the maximum net horsepower obtainable was equivalent to that of the test vehicle, and that this value occurred at the same percent of maximum engine speed as that of Figure 6. The relationship so obtained is given below.

$$P_N = -\ 27.703 + 0.08024N - 1.0895 \times 10^{-5}\ N^2 \qquad (49)$$

It was assumed that driveline efficiency for the test vehicle was the same as that for a pickup truck. The required constants, as given in Reference 38, for the variable driveline efficiency approximation are

$$e_f = 0.92$$

$$k = 0.041$$

From Equation 35, the engine horsepower expression for variable driveline efficiency becomes

$$P_E = 1.04415P_W + 0.03939P_N \tag{50}$$

To obtain some measure of confidence in the coefficients used to model wheel horsepower requirements, the top speed of the vehicle on level ground with throttle wide open was computed. The engine horsepower developed for this condition will be maximum (120 horsepower) and driveline efficiency will be 0.92. This indicates that the wheel horsepower delivered is 110.4. From trial-and-error solution of Equation 47, a maximum speed of 98 miles per hour was obtained. This value was considered realistic for the Ford Falcon.

Net specific fuel consumption in gallons per hour may be expressed as the following variation of Equation 30:

$$\text{nsfc} = \frac{V \times \text{gpm}}{P_E} \tag{51}$$

For a given speed and grade, engine horsepower is found through use of Equations 47, 49, and 50. Fuel consumption values obtained from Reference 13 for the same operating condition permit immediate solution of Equation 51. This was done for the Ford Falcon at numerous speed and grade combinations. In some cases involving negative grades, some means of resistance is required to hold the test speed, i.e., the vehicle will coast faster than the test speed unless restrained through braking, gear reduction, or both. Computationally, a negative value of engine horsepower and

consequently net specific fuel consumption results. Data for these cases are obviously not applicable for describing the map of net specific fuel consumption. Additionally, it was felt that speeds less than 30 miles per hour should not be considered because of the fixed-gear operation assumed. The variation of net specific fuel consumption with percent maximum net horsepower is shown in Figure 10 for several values of percent maximum engine speed. Because of the fixed-gear assumption, each curve actually represents a fixed vehicle speed. If the model used to estimate fuel consumption is correct, and if the Reference 13 data are correct, then the family of curves shown in Figure 10 should resemble that of Figure 9. Figure 10, however, differs from Figure 9 primarily because the variation of net specific fuel consumption with percent rated net horsepower output at a given engine speed appears to be made up of two intersecting curves in Figure 10. This behavior, also observed in an identical analysis of a 1964 Chevrolet, is not representative of automobile engine performance. It is noted that the minimum value of net specific fuel consumption consistently occurs at a grade of -2% (denoted by circles in Figure 10). The values shown for -2% grade are the cause of the uncharacteristic dips at the left side of each curve in Figure 10. The curves shown in Figure 10, plotted without the data at -2% grade, appeared smooth.

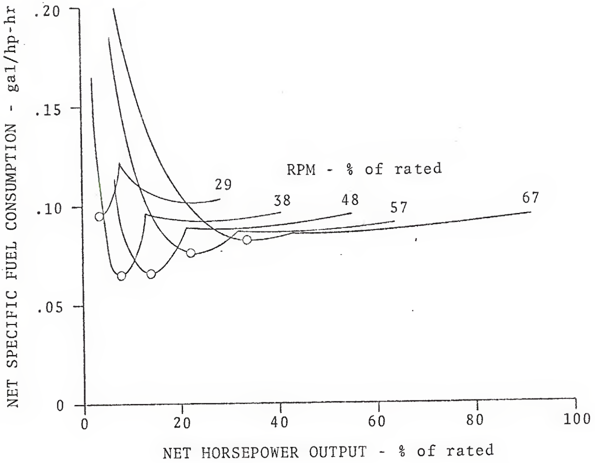

Figure 10 Simulated Net Specific Fuel Consumption Map

The behavior of the net specific fuel consumption map partly explains the failure of the four consumption models to represent the Reference 13 data, particularly at -2% grade. For example, the second degree polynomial in engine speed used to represent net specific fuel consumption in Model 4 could not possibly provide adequate representation of the curves shown in Figure 10, particularly at low engine speeds. This does not mean that the second

degree polynomial approach is wrong - other potential sources of error include oversimplified submodels of driveline efficiency and external forces as well as possible inaccuracies in the data used. The consumption data used were extracted from curves given in Reference 13. These data, presented in even 2-degree grade increments, were based on measurements typically made at different grades. Thus, some manipulation of data was required in the Reference 13 study in order to present it in even 2-degree increments. It is in no way implied here that the Reference 13 data are inaccurate. However, the regression techniques used to evaluate Models 1-4 are theoretically designed for use with measured data, and it is possible that had such data been available, the approaches taken would have had entirely different outcomes. It was felt that further attempts to model fuel consumption were beyond the scope of this dissertation, especially without raw data.

Energy data

Since an adequate mathematical model for fuel consumption could not be determined and composite automobile fuel consumption is relatively insensitive to changes in the automobile population, fuel-related energy requirements are based on Claffey's composite automobile data [13]. Placing these data on an energy basis requires an estimate of total primary energy per gallon of gasoline. The energy content of a gallon of gasoline was assumed to be approximately 127,900 BTU. However, the refining-transportation-sales

chain requires energy input such that the overall "ground-to-tank" efficiency is 0.812 [26]. Thus, the total primary energy used for gasoline is 157,500 BTU/gallon. This factor was used to convert Claffey's automobile fuel data to energy for all operating conditions.

Trucks

Fuel energy requirements for the 12,000-pound single-unit truck were computed from Claffey's data [13] for speed and grade combinations, horizontal curve configurations, and idle conditions. Since Claffey presents very little speed change data for single-unit trucks, Winfrey's values [16] were adopted. These consumption data were converted to energy terms at a rate of 157,500 BTU/gallon of gasoline. Data for the diesel-powered 3-S2 tractor semi-trailer combination were converted using Winfrey's consumption values and a factor of 176,400 BTU/gallon for diesel fuel. This factor was obtained under the assumptions that 1) the energy content of diesel fuel is 143,300 BTU/gallon and 2) ground-to-tank efficiency is the same as for gasoline, i.e., 0.812. Winfrey's 3-S2 data are used exclusively, as Claffey conducted no tests for this type of vehicle.

Maintenance

Energy required for vehicle maintenance is based on Winfrey's level tangent cost data for all three vehicles. Energy quantities were established using the I/O coefficient

for automobile repair and service updated to 1970 values. Winfrey's cost data were updated to 1970 using the factors given in Reference 43.

It was assumed that for a given speed, maintenance energy on grades and horizontal curves varied from level tangents at the rate of a fixed percent of the rate at which fuel consumption varied. The fixed percent used was 10% for the composite automobile and single-unit truck, and 20% for the 3-S2 combination. This approach is the same as that of Winfrey except that at negative grades requiring negative horsepower, Winfrey used a braking factor not defined. Maintenance energy for speed change cycles was based on the excess time required to make the cycle. Hourly rates of maintenance energy consumption were obtained by multiplying the initial speed by the maintenance energy consumption rate in BTU/mile for a level tangent. The product of the hourly rate obtained and the cycle time required is the maintenance energy required in excess of level tangent values. Cycle time values used were those of Winfrey.

Oil Use

Oil use in motor vehicles can be attributed to consumption by burning and leakage and to replacement due to contamination. Far more oil is used in oil changes than in actual consumption. While oil change intervals are usually based on mileage, these intervals are subject

to considerable personal judgment and are difficult to quantify. Claffey provides a limited amount of data for the variation of oil use due to consumption with speed. Winfrey [16], however, related total oil use to speed for level tangents. Normalized plots of Winfrey's automobile fuel consumption and oil use data with speed exhibit similar behavior.

Recent energy consumption studies indicate that on a national scale, passenger car oil use is about 1% of that of gasoline on an energy basis [16,26,51]. Because of the similarity in fuel consumption and oil consumption behavior with speed on level tangents, and because of the small oil-to-fuel energy use ratio, it was felt that energy consumed in oil use could be approximated as 1% of fuel energy without significant loss of accuracy for automobiles. Winfrey's oil consumption rates for the 12,000-pound single-unit truck and the 50,000-pound 3-S2 tractor semi-trailer combination were used directly. These data were converted to energy assuming that the total primary energy value for oil is equivalent to that of gasoline on a volume basis.

Treatment of the effects of grades and horizontal curves on energy required from oil use generally parallels that of Winfrey. It was assumed that the ratio of oil required at a given condition to that required on a level tangent at the same speed is the same as the equivalent fuel ratio. For the automobile, it was estimated that excess oil energy consumed in speed changes was 1% of the

fuel energy consumed. For both classes of trucks, the procedure used was the same as that for maintenance energy during speed change cycles.

Depreciation

Energy consumed in the form of depreciation is assumed to be directly proportional to monetary depreciation rate. It is considered that the energy quantity depreciable is equivalent to that of vehicle construction plus sales. As stated in Chapter III, the energy required to manufacture an automobile weighing approximately 4,000 pounds is 129×10^6 BTU. Using the 1970 sales energy values of Reference 12, the total primary energy required per automobile is about 165×10^6 BTU. Depreciable energy quantities for the single-unit truck and the 3-S2 combination are assumed to be proportional to that of the automobile on a weight basis.

The variation of depreciation energy with speed is based on Winfrey's data for level tangents. While no additional energy was assigned due to grades and horizontal curves, excess depreciation energy due to speed change cycles was estimated from excess time required to complete the cycle. The procedure is the same as that used for maintenance. It was assumed that depreciation energy consumed in idling is negligible.

Tire Wear

Tire wear energy is determined from dollar costs and

I/O coefficients updated to 1970 values. The total primary energy coefficient used for tires is based on an assumed markup of 40% of the manufacturer's cost [26] and 1970 cost data given in Reference 43.

Tire wear data for the composite automobile were taken from Claffey [13]. Winfrey [16] was the data source for both classes of trucks since Claffey did not present sufficient data for analysis of the single-unit truck. It is noted here that Curry and Anderson [43] are of the opinion that Claffey's automobile tire wear data on horizontal curves are exceptionally high, and they recommend use of Winfrey's data on curves and Claffey's elsewhere. Claffey's data on curves are used in this dissertation because 1) use of a consistent set of measurements is desirable and 2) Winfrey's data are primarily based on measurements made over 30 years ago. Winfrey's data are given for a broad class of high-type surface, while Claffey's data are given for two separate high-type surfaces - concrete and asphalt. The data used herein are based on asphalt, since it is most commonly used [43].

Claffey's automobile tire wear data are given in terms of speed on a level tangent and corrections are supplied for horizontal curves. Data for speed changes are given for stop-go cycles and 10 mile per hour cycles only. Excess tire wear for in-between cycles was assumed to vary linearly with magnitude of speed change. Claffey did not provide data for the effect of grades on tire wear, and these

effects were assumed to be negligible. Winfrey provides explicit tire wear data for level tangents only. The excess wear for horizontal curves and speed changes was estimated from his total cost data for these perturbations. Following his procedure for determining other cost items as closely as possible, tire wear costs were assumed to be the difference between total cost and the computed cost of all other items. The overall effects of any errors incurred in this process are much smaller for calculations based on energy than they would be for calculations based on dollars.

Accidents

The usual procedures for analyzing accident costs include figures for fatalities, non-fatal injuries, and property damage. The energy effects of injuries and fatalities are difficult to assess. For example, a fatality involves burial and possible hospital care. However, all people eventually die and at that time require burial, and hospital care may be involved beforehand. The net energy effect of a fatality, then, could be estimated as the energy a person would have consumed in the form of fuel, food, etc., between the time of his fatal accident and the time he would have perished by some other means. This implies that fatalities are road-user benefits and that roads should be made as unsafe as possible - an obvious absurdity. Similar arguments can be made for non-fatal injuries. Because of the conceptual

implications, it was decided to ignore injuries and fatalities in assessment of accident-related energy costs.

Energy consumed in property damage is computed from the I/O coefficient for automobile repair and service. Based on the property-damage-only data given in Reference 43, values of 7.54×10^6 BTU/accident on urban surface roads and 10.3×10^6 BTU/accident on rural surface roads and all freeways were computed. These data are for all accidents, including those not reported. The values should be multiplied by 2.5 if estimates are based on reported accidents only.

Travel Time

The energy value of personal travel time is zero. Since this factor usually plays a large part in monetary economic analyses, and since estimates of the value of personal time vary widely, some overall gain in accuracy of road-user cost calculations is realized in energy-based analyses.

An Observation

During preparation of the running cost tables, it was observed that the proportion of fuel energy requirements to total energy requirements varies considerably with regard to classification of energy cost. For example, at fixed speeds and grades, fuel energy typically amounts to about 80% of the total energy requirement, while for

speed changes, the combined requirements due to oil, maintenance, depreciation, and especially tire wear are about the same as for fuel.

CHAPTER VI

AN EXAMPLE

This chapter contains an energy-based benefit/cost analysis of a transportation project now under construction in Miami, Florida. It is felt that this project is particularly suited for demonstration of the methodology for the reasons enumerated below.

1) The project is "real world" rather than hypothetical.
2) Capital investments include both buses and roadway.
3) Analysis of modal shift to buses and carpools is possible.

Project Description

The State of Florida, in conjunction with federal and local agencies, and the University of Florida, is attempting to promote more efficient utilization of highway facilities in the I-95 corridor in Miami, Florida [52]. The project is being approached from the standpoint of efficiently moving <u>people</u> rather than vehicles. To accomplish this, two additional lanes are being constructed in the median of I-95 for exclusive use by buses and car pools during the morning and afternoon peak rush hours. These lanes, when completed, will extend from the Golden

Glades Interchange to the 36th Street Interchange (see Figure 11). Traffic demand in the project section exceeds capacity throughout both peak periods. A terminal and parking area at the Golden Glades Interchange will provide free parking for bus riders and car poolers.

Express buses will provide direct service from the Golden Glades Interchange to each of three central city destinations: the Miami International Airport, the Civic Center, and the downtown Central Business District (CBD). As a means of testing bus priority treatment on major arterial routes and as an immediate measure to relieve congestion created during construction of the additional lanes on I-95, the express bus service has been implemented on N.W. 7th Avenue, a major arterial parallel to I-95.

Alternatives and Assumptions

The analysis contained in this chapter considers the same project alternatives as the economic analysis performed by Robertson [53] for the same facility. Assumptions used in the energy-based analysis and that of Reference 53 differ significantly with regard to road-user costs - a more sophisticated approach is taken in the energy-based analysis.

Alternatives

The base alternative considered in this analysis, designated as Alternative A, is simply the existing facility. Construction and equipment investments for this alternative

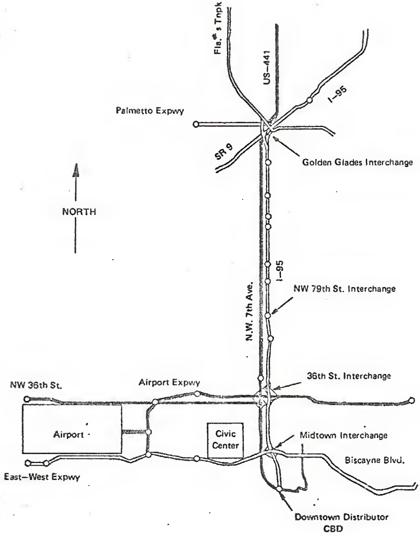

Figure 11 Major Project Facilities

are zero. Since benefits for alternatives will be computed relative to this base, running costs and costs of operations and maintenance are assigned values of zero.

Alternative B considers construction of the two median lanes for use by all vehicles during all periods. These lanes increase capacity by about 30%. The express bus/car

pool operation and the associated terminal facilities at the Golden Glades Interchange are nonexistent under this operational strategy.

Alternative C consists of construction of the median lanes, terminal facilities, and an information and enforcement system necessary for reserved lane bus/car pool operation. This alternative is evaluated for the following three combinations of modal shift: 5% to buses, 5% to car pools; 10% to buses, 10% to car pools; and 10% to buses, 15% to car pools. These combinations are designated C_1, C_2, and C_3 respectively.

Assumptions

The following assumptions are made for use in the energy-based analysis of each alternative:

1) Traffic growth rate is 5% per year.
2) The capacity of the mixed-mode lanes is 1,800 vehicles per hour.
3) Each of the two daily peak periods is 2 hours in length.
4) Normal vehicle occupancy is 1.3 persons per year.
5) The bus/car pool system will operate 255 days per year.
6) The effective length of the priority lanes is 7.6 miles.
7) Accident costs are the same for all alternatives.
8) The analysis period is 7 years.
9) Car pool occupancy is 3.0 persons per vehicle.
10) Average speed in the priority lanes is 55 miles per hour under free flowing conditions.

11) Speed/distance profiles from the end of the project section to each of the downtown destinations are the same for automobiles as for buses and are invariant with respect to both alternative and time.

12) The proportion of project trips to each downtown destination and the total trip length to each of these destinations are as shown in Table 17.

13) The difference between alternatives in energy consumption by trucks is negligible.

14) Road-user energy requirements are the same for the A.M. and P.M. peak periods.

15) Average bus headways are 3 minutes.

Table 17 Trip Proportions and Distances

From Golden Glades to:	% Trips	Distance (Miles)
Airport	39	12.9
Civic Center	43	11.3
CBD	18	12.3

Quantification of Terms

Construction and Equipment

Cost estimates for construction of the median lanes were obtained from Reference 52 and adjusted to 1970 price levels using the highway construction cost trend data of Reference 54. Using the total energy coefficient for urban interstate construction in Florida (see Table 4) and assuming a 20-year facility lifetime, an equivalent uniform energy requirement of 1.669×10^{10} BTU per year

was computed. This value is applicable to Alternative B but is common to alternatives C_1, C_2, and C_3. The three Alternative C combinations also require parking and terminal facilities, an information and enforcement system, thirty buses, and a "flyover" facility connecting the exclusive lane with the parking lot at the Golden Glades Interchange. The total equivalent uniform annual construction energy for the Alternative C combinations was found to be 2.194×10^{10} BTU per year.

Operations and Maintenance

Maintenance requirements of roadway-related items were assumed to be the same for Alternative B and the three Alternative C combinations. These requirements differ from those of Alternative A in that maintenance of the median under Alternative A is replaced by physical maintenance of the added lane under the remaining alternatives. The three Alternative C combinations also require maintenance and operation of both the information and enforcement system and some items associated with the express bus system.

The estimate of energy required to maintain the additional lane was based on the 25% increase in width required over most of the project section. This factor was applied to Table 5 data for the state of Florida and an equivalent uniform annual value of 0.042×10^{10} BTU per year was computed for roadway maintenance of the added lane in the project section.

The information and enforcement system required for the three Alternative C combinations is not usually found in highway projects and should be considered apart from normal operations and maintenance activities. Operation and maintenance energy requirements for the system were estimated based on the energy coefficient for operations given in Chapter IV and the system operations and maintenance cost data of Reference 52 modified to 1970 price levels. An energy requirement of 0.646×10^{10} BTU per year was computed.

Bus system energy requirements for items not directly associated with revenue equipment were determined using Equation 10. Solution of this relationship requires a knowledge of the total annual passengers using the system. From the initial facility demand and growth rate, an equivalent annual total demand of 6,889,225 persons per year was obtained. The number of vehicle miles traveled per year for the express buses is assumed to be 493,680. The requirements of bus system maintenance and operation thus determined are 0.515×10^{10} BTU per year for a 5% shift to buses and 0.529×10^{10} BTU per year for a 10% shift. Total operation and maintenance energy is estimated as 0.042×10^{10} BTU per year for Alternative B, 1.203×10^{10} BTU for Alternative C_1, and 1.217×10^{10} BTU per year for Alternatives C_2 and C_3.

Road-user Requirements

Proper analytical procedures require that the facility be divided into sections of relatively constant geometric and operational characteristics. These sections must in turn be evaluated to determine the critical section and any queueing that may exist or develop within it during the analysis period. Since the speed/distance profiles from the end of the additional lanes and the downtown destinations are assumed to be fixed, this portion of the study area is logically analyzed separately from the segment of I-95 affected by the added lane.

The existing facility contains three lanes in each direction from the Golden Glades Interchange to 135th Street and four lanes in each direction from 135th Street to the 36th Street Interchange. These sections are approximately 1.5 and 6.1 miles in length, respectively. Data taken in 1971 show that the three-lane section from the Golden Glades Interchange to 135th Street is the critical one in terms of volume-to-capacity (V/C) ratio during the A.M. peak [52]. The A.M. demand variation for this section was approximated by a linear buildup in demand with time to a peak value, a 15-minute constant peak demand value, and a linear decay in demand with time. The growth factor was used to scale this demand/time variation to the beginning of the analysis period and to each year within that period. This variation is shown in Figure 12 for the first year of the analysis period. It was found that under Alternative A,

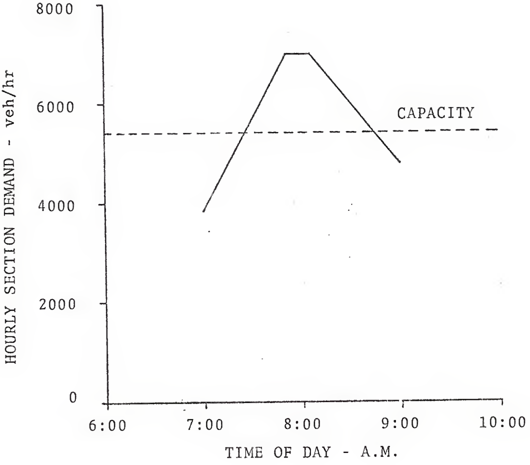

Figure 12 Demand/Time Variation in Critical Section (A.M.) for First Analysis Year

the average demand-to-capacity ratio during the A.M. peak is greater than one even for the first year of operation. This implies a queueing condition since the flow of vehicles through the section is restricted to the value of capacity. The section must operate at capacity for some time period after demand has dropped below capacity in order to dissipate the queued vehicles. Once the queue is dissipated, the section operates at a V/C ratio equal to the demand-to-capacity

ratio. It is necessary to analyze the effects of queueing throughout operation at capacity, even though these effects extend past the end of the peak period under investigation, since speed and speed changes are related to operating V/C ratio and will therefore vary between alternatives. That is, for each year the time of day that analysis can be terminated is defined to be the latest time of day among all alternatives that queueing effects cease. The alternative defining these end points is always Alternative A because all other alternatives are based on an additional lane and thus consistently operate at lower demand-to-capacity ratios. While the added lane would theoretically have an operational effect throughout the day, it was assumed that average off-peak V/C ratios are low enough that these effects are negligible. The area of the demand curve above the capacity line represents the number of queued vehicles present at the time demand has dropped to the value of capacity. Similarly, the reduction in the number of queued vehicles between this time and some time, t, is represented by the difference in area between the capacity line and the demand curve. These two areas are disignated in Figure 13 as A_1 and A_2, respectively. The time at which the effects of queueing end is that time at which A_1 and A_2 are equal. This time was determined for each analysis year for Alternative A. Road-user analyses for this and all other alternatives were based on conditions from the beginning of the peak period (assumed to be 7:00 A.M.) until

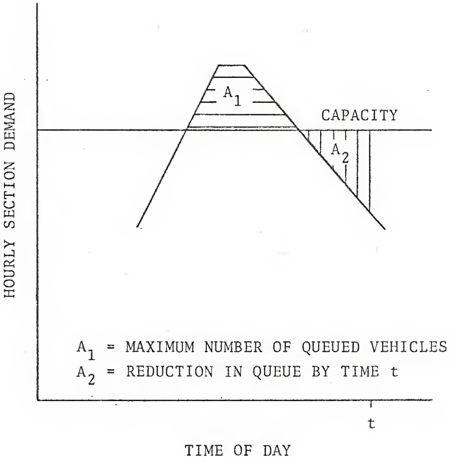

Figure 13 Pictorial Description of Queue Development and Dissipation

these end points were reached. For the three Alternative C combinations, it was assumed that reserved lane operation was terminated at the end of the peak period and that the added lane was then available for use by all vehicles. Since it was considered that express bus operation ceased at the end of the peak and that average auto occupancy subsequent to that time was 1.3 persons per vehicle, this

change in reserved lane status effectively increased both capacity and the rate of queue dissipation.

Road-user energy requirements for the critical section are caused by speed, speed changes, and for queued vehicles, a stop-go speed change cycle and idling during the delay. Values of speed as a function of V/C ratio for freeways were taken from Reference 43. Since the section is essentially flat and straight, energy requirements at a given speed were obtained from Table 7 at zero grade.

Curry and Anderson [43] present data which indicate a linear relationship between dollar costs due to speed changes and V/C ratio for various classes of highways. Comparison of the total running cost data and the speed change data given in Reference 43 for freeways indicates that for a V/C ratio of 1.0, dollar costs of speed changes are approximately 7% of running costs at the same speed without speed changes. As a first order approximation, it was assumed that energy requirements due to speed changes vary in the same manner. This approximation results in a speed change energy requirement due to traffic interaction of 593 BTU per mile for a V/C ratio of 1.0 decreasing linearly to 0.0 BTU per mile for a V/C ratio of 0.0.

Vehicles experiencing queueing were each assigned one stop-go speed change cycle in addition to the idling energy consumed while the vehicles are at rest. The number

of vehicles experiencing this speed change cycle are all of those arriving at the critical section between the time demand exceeds capacity and the time queue dissipation is complete. Idling energy during queueing was determined from the idling energy consumption values of Table 16 and the total vehicle-hours of delay experienced under queueing conditions. Total delay for uninterrupted flow was computed as the area between the cumulative demand curve and the cumulative critical section flow curve defined by the value of capacity during the queueing period, as shown in Figure 14 for a constant capacity configuration.

The section downstream of the critical section was analyzed using the same procedures previously described. Since the downstream section has one more lane than the critical section and the demand was assumed to be the same, it was not necessary to consider queueing. That is, the flow in the downstream section is assumed to be no greater than the capacity of the critical section and a lower V/C ratio is experienced due to the extra lane.

Speed/distance profiles from the freeway to each of the downtown destinations were quantified from data recorded during peak period operation. Measuring devices placed on the express buses (which operated on the freeway in 1974 for a short time without priority lanes) were used to record time values for every 107-foot subsection traveled. Average speed in these small subsections was computed by dividing the distance traveled by the time spent in traversing it.

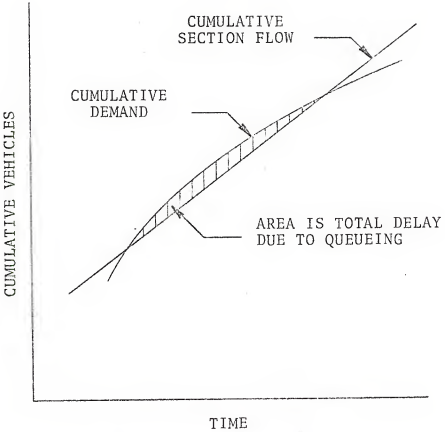

Figure 14 Representation of Total Delay Due to Queueing

For the data examined, it was found that smooth flowing conditions at an average speed of 40 miles per hour were obtained on I-95 south of the 36th Street Interchange. Sectioning was performed for each route relative to the point where these conditions changed and the end of each route. These sections and the operating conditions observed for each are summarized in Table 18 for the three routes.

Table 18 Section Operating Characteristics for Downtown Routes

Route	Item	Section 1	Section 2	Section 3
Airport	Section length (mi)	2.452	1.621	-
	Speed (mph)	45	25	-
	Number of 10 mph speed changes	3	1	-
	Number of stops	1	5	-
Civic Center	Section length (mi)	1.094	-	-
	Speed (mph)	20	-	-
	Number of 10 mph speed changes	3	-	-
	Number of stops	4	-	-
CBD	Section length (mi)	0.507	1.013	2.493
	Speed (mph)	30	15	30
	Number of 10 mph speed changes	1	0	1
	Number of stops	1	4	2

Buses were assumed to either deadhead back to the Golden Glades Interchange to pick up additional passengers or, at the end of reserved lane operation, travel to some other location for servicing routes not associated with the project. These energy requirements were assumed to be the same as those for a one-way project trip.

Total road-user energy requirements were computed relative to Alternative A. For Alternative B, there is no shift to buses and car pools and under the stated assumptions, there would be no difference in energy requirements south

of the additional lanes. For the three Alternative C combinations, a savings (negative cost) exists in this area due to the number of automobile trips eliminated by the shift. At the same time, the bus operation produces a positive cost. The sum of these costs define the savings for these trip portions relative to Alternative A.

Analysis of Alternatives

The equivalent uniform annual energy costs attributed to construction and equipment, operations and maintenance, and road-users are assembled relative to Alternative A in Table 19 for all alternatives considered. The nomenclature used is that defined in Chapter II. The multiplier, 10^{10}, is common to all terms and may be omitted in benefit/cost ratio calculations.

The first analysis of alternatives considers Alternative B as challenger and Alternative A as defender. Benefit/cost ratios are computed using the expression given in Chapter II.

$$B/C = \frac{-\ (U_P - U_B)\ -\ (K_P - K_B)}{-\ (\frac{I_P}{L_P} - \frac{I_B}{L_B})}$$

Substitution of the appropriate values from Table 19 give

$$B/C = \frac{-\ (-27.295 - 0.0)\ -\ (0.042 - 0.0)}{-\ (1.669 - 0.0)}$$

Appropriately ignoring the sign of the denominator,

$$B/C = 16.33$$

and Alternative B is preferred. The second comparison

is made with Alternative B as defender and Alternative C_1 as challenger. The benefit/cost expression is

$$B/C = \frac{-(-29.064 + 27.295) - (1.203 - 0.042)}{-(2.194 - 1.669)}$$

which, with proper signing, becomes

$$B/C = 1.16$$

While this ratio indicates a preference for Alternative C_1, its magnitude is sufficiently close to one to classify it as marginal. Should Alternative C_1 become the preferred alternative among all candidates, the proper analytical procedure would be to revaluate the assumptions made to insure a conservative result. For this particular analysis, however, the indication is that this particular modal shift approximately represents the shift required to justify using the added lane for buses and car pools rather than in a mixed-mode fashion. That is, for a modal shift less than the values given for Alternative C_1, the preferred alternative would likely be Alternative B.

It is noted that all three of the Alternative C combinations actually represent variations of a single alternative under different operating conditions. The differences in these three operating conditions are due to modal shift alone - something over which the decision maker has no control. Analysis of these shifts, then, should logically be made with respect to another general alternative rather than with respect to themselves. Indeed, benefit/cost ratios of the three Alternative C combinations

Table 19 Summary of Costs

Alternative	Costs (BTU/year x 10^{-10})		
	I/L	K	U
A	0	0	0
B	1.669	0.042	-27.295
C_1	2.194	1.203	-29.064
C_2	2.194	1.217	-40.989
C_3	2.194	1.217	-44.648

computed relative to one another are of infinite magnitude since the common construction and equipment energies cause the denominator of the benefit/cost ratio to become zero. For this reason, the remaining alternatives (C_2 and C_3) will be compared with Alternative B. Substituting the proper values from Table 19 into the benefit/cost relationship gives

$$B/C = \frac{-(-40.989 + 27.295) - (1.217 - 0.042)}{-(2.194 - 1.669)}$$

for the comparison of Alternatives C_2 and B. The final result is

$$B/C = 23.85$$

and Alternative C_2 is preferred. The final comparison is made between Alternatives C_3 and B. Appropriate Table 19 values are again substituted into the benefit/cost expression and the following is obtained:

$$B/C = \frac{-(-44.648 + 27.295) - (1.217 - 0.042)}{-(2.194 - 1.669)}$$

$$B/C = 30.82$$

and Alternative C_3 is preferred. Analysis of the Alternative C combinations, then, show each to be superior to Alternative B, but by differing amounts. A decision maker could now compare the general Alternative C with Alternative B based on <u>expected</u> values of modal shift and assess the consequences of any variation in magnitude of this expected shift that might occur in actual operation. For example, if the expected shift is 10% to buses and 10% to car pools (Alternative C_2), he would know that the reserved lane operation would still be marginally profitable if only half of that shift occurred (Alternative C_1).

The energy-based rate of return can be determined for any alternative using the expression established in Chapter II. As an illustration, the energy-based rate of return for Alternative C_3 is computed. First, a benefit/cost ratio is computed with Alternative C_3 challenging Alternative A. The result of this calculation is

$$B/C = 19.80$$

The energy-based rate of return is expressed as

$$EROR = B/C - 1$$

or

$$EROR = 18.80$$

This implies that under the stated assumptions, a shift of 10% to buses and 15% to car pools will generate an energy

savings nearly 19 times as large as the annual equivalent of the energy required to construct the facility and express buses.

The auto occupancy factor of 3.0 assumed for car pools is considered to be the minimum acceptable value for reserved lane operation, although this analysis considered the average value to be 3.0. The effects of a higher occupancy factor (4.0) on running costs were studied. This occupancy factor is probably higher than that which can actually be achieved and is assumed to be an upper bound. This 33% increase in car pool occupancy was found to cause errors in running costs relative to Alternative A (the U values in Table 19) of only 1.6%, 2.3%, and 3.2% for Alternatives C_1, C_2, and C_3, respectively. Thus, the benefit/cost ratio calculations are essentially insensitive to car pool occupancy factor.

The energy-based benefit/cost ratio magnitudes computed in this analysis are much larger than those of the Reference 53 economic analysis, and the stepwise procedure in that analysis indicated a preference for Alternative B over all candidates except Alternative C_3. However, it is noted that the running cost assumptions used in Reference 53 are much simpler than those of this analysis.

CHAPTER VII

CONCLUSIONS

A simple goals-achievement analysis was used to assess several candidate criteria for use in determining the feasibility of transportation projects. The criterion which at least partially satisfied all stated goals, energy-based benefit/cost ratio, was recommended for use. Quantification of each of the benefit/cost ratio terms on a net energy basis, then, is all that is required for stepwise comparison of proposed project alternatives. The numerous tables and formulae developed make this quantification possible for projects involving highway vehicles, including those for which bus rapid transit is considered as a capital investment. The user-oriented data format is intended to permit as much use as possible of project data required for traditional economic analyses. The technique was applied to a bus/car pool systems demonstration project now being conducted in Miami, Florida.

The accuracy of the tables and formulae developed is to some extent unknown; however, some comments regarding the differences in energy-based and economic analyses are in order. The tables and formulae presented in this dissertation are largely based on the same techniques and

assumptions as those used in economic analyses. For example, the contribution of tire wear, maintenance, and depreciation to total running cost energy requirements are based as much as possible on the same speculative assumptions used in what appear to be the most widely accepted data sources in that area. With the exception of roadway construction and maintenance energy requirements, errors due to use of differing assumptions should indeed be small; and comparison of highway construction model-generated data with economic I/O data at the national level tended to verify the adequacy of that model. It is noted that two factors which play a large role in the outcome of economic benefit/cost ratio calculations are absent in the energy-based approach. These two factors are vestcharge rate and the hourly value of personal time during travel, both of which are based largely on judgment. In practice, the values for these items sometimes vary widely between analyses, especially the value of travel time. The absence of these factors in energy-based analyses leads one to expect a higher degree of accuracy for that approach than for economic analyses. However, the accuracy of the energy-based approach is limited throughout by the inherent inaccuracies resulting from the degree of disaggregation of the U.S. economy in the I/O tables on which energy values are based and by the uncertainties involved in forecasting the time variation of energy-based I/O coefficients. Hirst

and Herendeen [12] estimate an upper limit on the accuracy of energy-based I/O coefficients at $\pm 20\%$. Because of the different major sources of error involved in the energy-based and economic approaches, no firm conclusion can be drawn as to their relative accuracies. There is no reason to believe, however, that the energy-based approach is significantly inferior to the economic approach from an accuracy standpoint.

The example analysis described in Chapter VI indicates that values for energy-based benefit/cost ratios may be considerably different from those for economic analyses. This implies that an energy-based analysis could be very influential in the decision-making process, especially in situations where two alternatives are nearly equal in all other respects. The energy-based benefit/cost ratios determined in the Chapter VI analysis were fairly large. An assessment of car pool occupancy showed that a change in average occupancy from three to four persons per vehicle affected running costs only slightly relative to the do-nothing alternative (typically less than 3%). This indicates that for this particular project, the vast portion of the energy savings achievable arises from the auto-to-bus shift - a result that is not too surprising.

The magnitudes of relative road-user energy costs between alternatives in comparison with those for capital investments and operations and maintenance in the example study (see Table 19) tend to illustrate the importance of operational improvements and the accompanying potential for

energy savings. Of the items which make up road-user energy costs, automobile fuel consumption is the one most significant. For constant speed situations, it was observed during preparation of the running cost tables that fuel requirements typically made up about 80% of the total running cost energy. Similarly, it was noted that for speed change energy, the combined requirements of oil, maintenance, depreciation, and most importantly tire wear were about the same as for fuel. This is significant in that some consideration has been given to retiming traffic signals to minimize fuel consumption. A minimization of total energy consumption would be considerably more appropriate.

Attempts to model fuel consumption were unsuccessful, apparently due to measured values at -2% grade which imply better mileage on slightly rolling terrain than on level terrain. This difference could not be resolved with theory, and a reverse-type analysis to ascertain the engine performance characteristics required to produce this phenomenon showed unrealistic behavior. The cause of the uncharacteristic trends was attributed to consumption values at -2% grade. The phenomenon is still unexplained.

It is felt that the work presented herein represents the limit of the level of detail practical for energy-based analyses of transportation improvements at this time. New economic I/O tables (for 1967) should be available and presumably will be used to generate a new set of

energy-based I/O data. Considerable insight may then be gained as to timewise variations of these coefficients. Furthermore, an assessment could be made of the assumption frequently used in this work that energy requirements based on physical properties are relatively constant over time.

Much more work is needed in the area of running cost quantities, especially for fuel consumption. Hirst [51] shows that on a large scale, fuel consumption varies greatly with trip length due to the effects of "cold starts," i.e., automobile fuel consumption is significantly lower for a warmed-up engine than for a cold one. This factor is not considered at all in benefit/cost analyses, but it apparently should be. No data are available, however, by which the effects of cold starts on consumption under different roadway conditions can be assessed.

This work was prompted partially because of the large amount of petroleum fuel energy required for highway transportation and the growing scarcity of that energy source. It is felt that the general approaches used could be extended to both other transportation modes and to vehicles under development which will be used in the future.

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BIOGRAPHICAL SKETCH

Jamie Woodrow Hurley, Jr. was born on December 20, 1939 in Memphis, Tennessee. He attended public schools in Tennessee and Mississippi and was graduated from Provine High School, Jackson, Mississippi in June 1957.

In September 1957 he enrolled at the Mississippi State University and received the Bachelor of Science degree in Aeronautical Engineering in August 1961.

From September 1961 to July 1962 he was employed as an Aerospace Engineer by the U.S. Army Missile Command, Redstone Arsenal, Alabama where he was involved in evaluation of Army missile systems reliability.

In July 1962 he accepted a position with the George C. Marshall Space Flight Center, Huntsville, Alabama where, as an Aerospace Engineer, he was primarily engaged in aerothermodynamics research and development.

He entered the Graduate School at the Mississippi State University in September 1965 and was awarded a Graduate Research Assistantship in the Department of Aerophysics. He received the Master of Science degree with major in Aerospace Engineering in January 1967.

From September 1966 to September 1971, he was employed as a Senior Engineer by the Boeing Company in Huntsville,

Alabama. In September 1967 he was assigned the position of Lead Engineer of Boeing's Targeting and Space Trajectories Group.

In September 1971 he enrolled in the Graduate School at the University of Florida and began work toward the Doctor of Philosophy degree with major in Civil Engineering and emphasis on Transportation. He has held Graduate Assistantships with the Department of Industrial and Systems Engineering, the State University System of Florida, and the Department of Civil Engineering.

Jamie Woodrow Hurley, Jr. is married to the former Linda Judith Mahan. He is a member of the Transportation Research Board, the Institute of Traffic Engineers, and the Mississippi State University Alumni Association. He is a 32° Mason and a Shriner.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Joseph A. Wattleworth

Joseph A. Wattleworth, Chairman
Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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